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Silt Fences to Control Sediment Movement on Construction Sites

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Abstract:	Environmental concerns regarding erosion control at construction sites are gradually rising. As a result, there is a recurring need to evaluate the state-of-the-art with respect to the use of silt control structures. The purpose of silt barriers is to trap sediments before they can enter a stream or lake and cause damage directly to aquatic life or the aquatic environment sustaining life. Regardless of the material used in the construction of silt barriers, the primary mechanism for removing sediments is through the ponding of water, which allows sediments to settle out. The effectiveness of silt barriers is primarily due to the ability of the barrier to cause ponding while remaining pervious enough to pass the incoming water. Silt barriers are not filters in the sense that the sediment is trapped on the geotextile or other material. If the pore size is small enough to retain a given sediment, rapid clogging of the barrier results with almost certain failure of the silt barrier by overtopping. Endorsing textbook methods for sediment control at construction sites, and re-emphasizing the need for proper installation are the most important results of this study.
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ABSTRACT

Environmental concerns regarding erosion control at construction sites are gradually rising. As a result, there is a recurring need to evaluate the state-of-the art with respect to the use of silt control structures. There is a well-developed literature dealing with silt control methods, including two books providing design information and a number of manuals providing detailed design and installation procedures. However, the methods often fail and this study was undertaken to investigate the reasons for failures and to provide some recommendations for the improvement of current practices.

The purpose of silt barriers is to trap sediments before they can enter a stream or lake and cause damage directly to aquatic life or the aquatic environment sustaining life. Regardless of the material used in the construction of silt barriers, the primary mechanism for removing sediments is through the ponding of water, which allows sediments to settle out. The effectiveness of silt barriers is primarily due to the ability of the barrier to cause ponding while remaining pervious enough to pass the incoming water. Silt barriers are not filters in the sense that the sediment is trapped on the geotextile or other material. If the pore size is small enough to retain a given sediment, rapid clogging of the barrier results with almost certain failure of the silt barrier by overtopping.

Through a series of laboratory tests, various commonly used silt barrier materials were subjected to a sediment laden flow. The results indicated that, providing the material is able to restrict the flow to cause ponding, the sediment trapping efficiency is not dependent on the material used. When the ponded water becomes totally filled with sediment, all silt barriers fail, irrespective of the material employed. As a medium, straw bales are as effective as geotextiles or gravel berms but straw is much more difficult to install properly.

To have any degree of success with silt barriers, proper design, installation, and maintenance are needed. In virtually all failures referred to in the literature, the failure was due to the improper installation of the silt barrier. Unless the barrier is properly installed with regard to every detail, there is no point in installing the barrier at all. The most important result of this study is to endorse textbook methods for sediment control at construction sites, and to re-emphasize the need for proper installation. In the context of Ontario Ministry of Transportation construction projects, the need for adequate construction specifications, for on-site inspection, and appropriate financial incentives for the contractor are obvious.

1. INTRODUCTION

It is nearly impossible to carry out any major construction project such as the construction of a road or bridge without some significant disruption of the local drainage regime. This may include the removal of vegetation and topsoil over a large area and the relocation of drainage channels. The first leaves the soil unprotected from rain and/or wind erosion while the second often improves the sediment carrying capacity of the drainage system. In general, the larger the exposed area, the longer the time the area is unprotected by vegetation, and the steeper the slopes, the greater the problem. Unprotected, a construction site can introduce large amounts of silt into receiving water courses with highly undesirable effects, such as smothering aquatic vegetation, clogging gravel beds, and raising the turbidity levels in the stream with consequent environmental effects on other forms of aquatic life.

Environmental concerns regarding erosion control at construction sites are gradually rising. The population increasingly views the destruction of fish habitat as undesirable, if not intolerable. Furthermore, since there is detailed information available on how to prevent environmental damage as a result of sediment production on construction sites, it appears unnecessary that any damage to the environment should occur at all, with the exception of damage caused by rare events. Considering the points listed in the previous paragraph, the obvious first consideration in erosion control should be to minimise the time that soil is left unprotected by vegetative or other cover. However, since it cannot be reasonably expected that any exposed area be immediately protected without adding a great deal to the cost of construction, it is generally accepted that sediments will be produced at construction sites but that sediments must be controlled on site.

As a result, there is a recurring need to evaluate the state-of-the-art with respect to the use of sediment or silt control structures. There is well-developed literature dealing with silt control methods, including two books providing design information and a number of manuals providing detailed design and installation procedures. However, the methods often fail and this study was undertaken to investigate the reasons for failures and to provide some recommendations for the improvement of current practices.

2. HYDRAULIC BEHAVIOUR OF SILT FENCES

The purpose of silt barriers is to trap sediments before they can enter a stream or lake and cause damage directly to aquatic life or the aquatic environment sustaining life. The primary mechanism for trapping sediments is through creating a pond, which allows sediments to settle out. It is not practical to remove particles finer than 0.02 mm (medium silt) because of the long time requirement for settling (Goldman et al., 1986).

In river flows, two types of sediment are generally recognised: bedload and washload. As the name implies, the bedload consists of soil particles which are intermittently moved from one resting point on the bed to the next through a series of "hops". It is these particles which also make up the bed of a river, stream, or ditch. One of the most difficult areas of hydraulic engineering involves the prediction of resistance from such beds, because of the resulting bedforms: riffles, flat beds, dunes, and on very steep slopes, antidunes. These bedforms and mechanisms are described in standard river engineering textbooks, such as Henderson (1966). Bedload is relatively easy to trap - it merely requires some ponding of the stream and the material will be trapped until the pond becomes filled with the trapped material.

The washload is much more difficult to trap. It consists of very fine particles which are carried in suspension by the flow. These particles are often the clay and organic particles in the soil and are characterised by a very low settling velocity. On construction sites it is often not practical to trap these particles. Filtering is ineffective because a very fine mesh would be required. This would cause early clogging of the mesh, and the surface area of screen needed to pass the flow would render barriers impractical. The only other method available would be a large settling pond. Unless land is available to create such a pond, and/or such a pond can become a permanent facility, this method is not practical either. Water treatment plants do employ settling tanks to remove clay particles but this is with the aid of chemical flocculation agents. However, while the washload can be detrimental if the runoff from the construction site is to a clear lake or stream, it may often not add substantially to an existing washload, and moderate amounts of fine sediments added to a stream for short periods may not be detrimental to aquatic habitat or life. The only practical measure to reduce the influx of the finest particles to the stream is to reduce the exposure of the soil to erosion.

In summary, the silt-laden water must be ponded in some manner to allow for settling of the soil particles before conveyance to an existing water course. Such structures can be sediment

basins or traps, straw bale barriers, silt fences, combinations of these three, or any means to temporarily store water allowing silt particles to settle to the bottom. A comprehensive survey is provided by Goldman et al (1986).

2.1 Feasibility of Collecting Sediments in Drainage Water

As mentioned earlier, there are two types of sediment load in a sediment laden-flow: bedload and washload. Usually, particles smaller than 0.062 mm are classified as silt or clay (Simons and Senturk, 1977). For these smaller particl , Stokes law applies, resulting in a fall velocity approximately proportional to the particle diameter squared. For the larger particles, the fall velocity, or settling velocity, is proportional to the square root of the diameter. As a result, the velocity required to move clay is much smaller than the velocity required to move sand (Simons and Senturk, 1977), implying that very low velocities are required to remove clay from a flow. Goldman et al. (1986) provide a table of particle size versus the surface area required to remove that particle size in a settling pond. The data has been plotted in Figure 1.

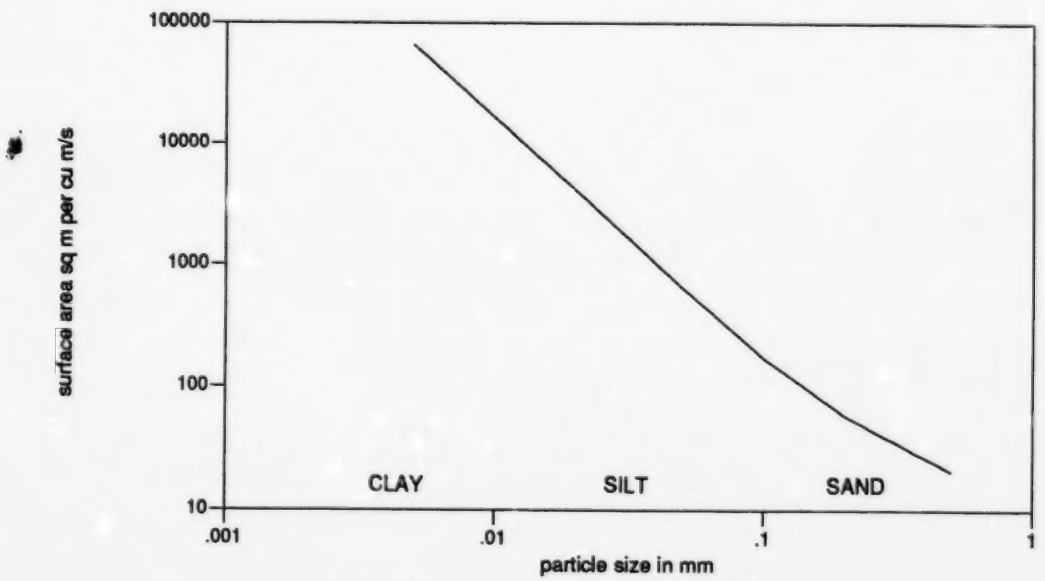


Figure 1 - Surface area requirements of sediment traps and basins
(Data from Goldman et al., 1986)

Figure 1 shows that to remove a coarse silt/fine sand from the effluent of a 4000 m^2 drainage area (approximately 1 acre), a 35 m^2 detention pond would be required for the two year return interval rainfall. To remove a fine silt, over 1000 m^2 of pond surface is required, which is approximately 1/4 of the area drained. From these numbers, it is obvious that it is not practical to remove particles much finer than a medium silt without creating substantial sedimentation ponds, with associated outlet structures. For comparison, a silt barrier which ponds the water to 0.5 m in a ditch with a 0.5% slope and 1:3 side slopes would result in a surface area of 300 m^2. This would be large enough to remove a coarse silt (0.05 mm) from a 0.4 ha (1 acre) area for the two year event. The interesting question which now arises is whether the escaping fine silt and clay would harm the receiving water body should a rainfall event occur during the construction period. Because such fine materials do not readily settle out anywhere, will they not disperse to sufficiently low concentrations in the receiving stream, which presumably will also have an increased flow during a rainfall event?

This study does not address these latter questions. It is limited only to studying the effectiveness and suitability of various materials for use as silt barriers.

2.2 Sediment Accumulation in Ponds

Koerner (1984, 1985) has sections on the design of silt fences in his books based on a theoretical development by Bell and Hicks (1984). Figure 2 shows a profile of a sedimentation pond. Quoting Koerner directly:

> "The physical model utilised in the theoretical development has sediment carrying runoff water depositing soil particles within and on the surface of the fabric as it first acts as a true filter, then eventually clogs in its lower part so that the water can no longer pass freely through it. The reservoir created by this action causes the coarse sediment to settle behind the clogged silt fence and the water carrying particles to try to reach higher levels of the silt fence itself above the clogged region. With time, an equilibrium is established."

While the method presented by Koerner appears sophisticated, it does not present a method to calculate H, the height to which the fence is clogged. There does not appear to be any method by which this height can be predicted for a particular situation because of the essentially unpredictable nature of the incoming sediment. If this is indeed the case, it renders the method useless.

A series of experiments were conducted at the University of Waterloo for this study. The

experimental setup will be described in detail later, but a few introductory remarks about the sedimentation pattern observed in the laboratory at this point will aid in understanding some of the recommendations regarding the installation of silt barriers found in the literature.

Figure 3 shows the successive surface profiles of collected sediment and the water surface in front of a silt barrier in the laboratory. Notice that the sediment is first deposited at the point where the water velocity is first reduced by the ponding due to the silt barrier. These deposits originated from the bedload and the deposition pattern is a delta formation process. The ponded volume is gradually filled with sediment until the toe of the sediment deposit reaches the obstruction.

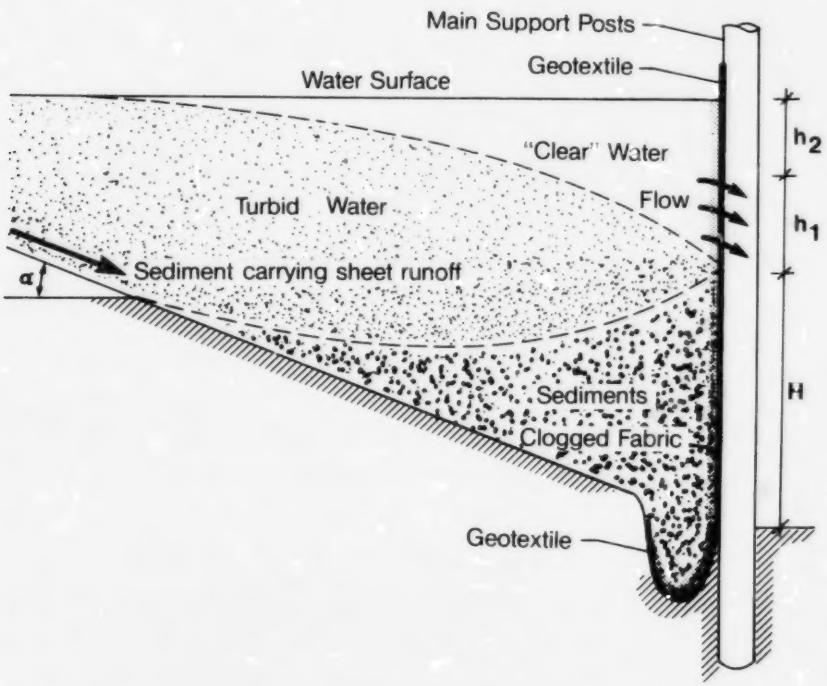


Figure 2 - Successive water and sediment profiles
(Koerner, 1984)

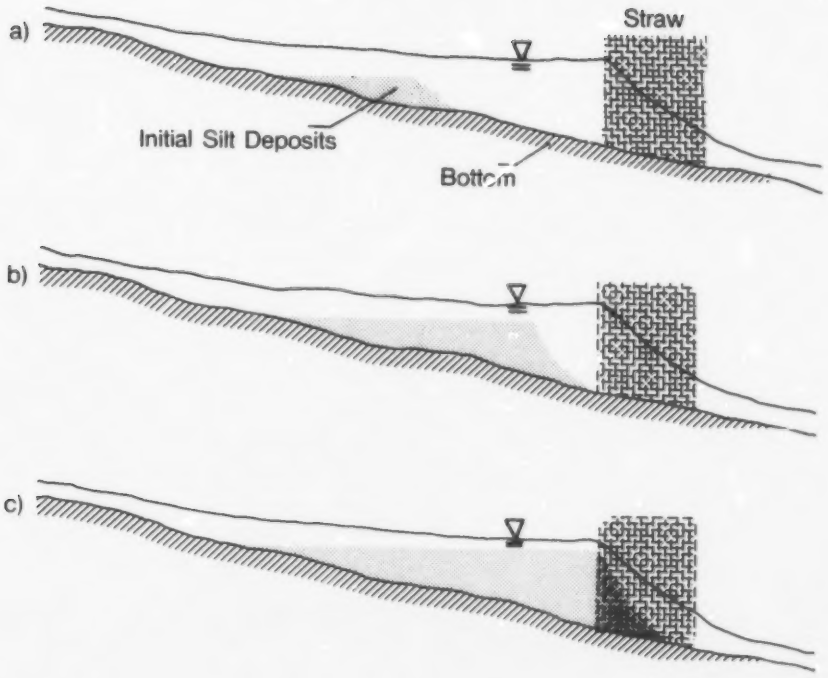


Figure 3 - Sequential water and sediment profiles

At this point, if the pore size of the barrier is small enough to block the passage of the sediments and if the filter is not already clogged, the sediment will build up in front of the barrier, gradually clogging the covered material, and thus raising the water level upstream. This raised water level causes more sediment to drop out at the upstream end of the pond.

While both the Bell and Hicks (1984) model and the above model of sediment accumulation are valid, it is questionable if the Bell and Hicks model can be applied to conditions in Ontario. The limitation to pond size as discussed above applies no matter where the location, and if

coarse silt or larger particles are considered, the delta formation process is dominant. The primary consideration then in the design of a silt barrier is to prevent overtopping of the barrier due to clogging and yet cause a sufficient ponded water volume to trap the sediment.

2.3 Design and Construction of Sediment Traps

For the sake of the following discussion, the purpose of silt barriers (including check dams made of straw bales, gravel berms, brush, or combinations of these with and without geotextiles) is to reduce the velocity of flow to allow for the settling of sediment to the bottom. This is accomplished by temporarily ponding run-off. Four typical types of check dams used as temporary erosion control methods are: (Goldman et al, 1986)

1) Straw bale barriers
2) Silt fences (filter fabric attached to a wire fence)
3) Filter fabric on straw bales or piled brush
4) Gravel and earth berms

Instructions for the proper design and installation of sediment barriers are already given in the "Guidelines on Erosion and Sediment Control for Urban Construction Sites" published by the Ontario Ministry of Natural Resources and in "Erosion and Sediment Control", Chapter F in the M.T.C. Drainage Manual, published by the Ontario Ministry of Transportation. The following sections provide a brief review of these items.

2.3.1 Straw Bale Check Dams

Straw bale barriers require replacement every three months and their trapping efficiency is reported to be less than 20%. (Goldman et al, 1986) This type of barrier is made up of entrenched, tightly abutted straw bales end to end which are staked down to maintain their position. Combining this barrier with filter fabric is most effective, as it compensates for the shortcomings of each material. However, such a structure is more expensive than either material used separately.

2.3.2 Silt Fences (geotextiles attached to wire fence)

The advantages of silt fences are: (Goldman et al, 1986)

1) They can last longer than six months (some maintenance required);
2) They are more effective (trap a higher percentage of sediment than straw bales) due to stronger construction, greater depth of ponding, and a trapping efficiency greater than 75%;
3) They can be preassembled;
4) They are relatively inexpensive.

2.3.2.1 Applications of Silt Fences

There are several applications for silt fences. They can be used to protect storm drain inlets from infiltration of silt which can clog drainage systems. Silt fences are often used at the toe of fills containing highly erodible soils. They are used along sidewalks, roads, and waterways to prevent silt from reaching these respective routes. They can be applied as a perimeter control for a construction site. Silt fences can also be used across small drainage ways to prevent sediment from flowing into drains. (Martin, 1985)

When designing silt fences, one must be aware of the limitations that exist. Silt fences are only meant for sheet flow run-off. Where they are used for drainage, the velocity and volume of flow must be low. The most realistic particle size that can be filtered are medium silt-sized particles (Goldman et al, 1986), although some clay size particles will be trapped due to the formation of a filter cake on the face of the silt fence. Four main limitations are:

1) Drainage area must be less than 0.4 ha (1 acre);
2) Maximum slope behind the barrier is 2:1;
3) Maximum slope length upstream of the barrier is 30 meters;
4) When placed across a small swale, the barrier should not receive concentrated flows greater than 0.028 m^3/s (1 cfs).

Where these limitations cannot be met, special design alternatives may still allow its usage, or conventional sediment trapping techniques such as sediment basins and traps will be required. (Goldman et al, 1986)

In the past decade, several problems with regard to silt fence failure have been encountered. These include undercutting, end runs, holes/tears, and fence collapse. The design engineer should be aware of the causes and consequences of such failures and incorporate measures in the design to ensure their prevention and solution when encountered.

Selecting the proper geotextile for the silt fence requires determination of the performance requirements:

1) filtering efficiency
2) slurry flow rate
3) strength
4) ultraviolet sensitivity
5) resistance to environmental factors (rot, rodents, and commonly encountered chemicals)

The fabric must retain soil yet permit drainage and prevent clogging. It must also be able to withstand installation stresses, and stresses induced by its functioning. Martin (1985) suggests that filtering efficiency is attained by choosing the proper EOS (Effective Opening Size) of the geotextile which would depend on the soil conditions. Martin further suggests that an opening size larger than the largest soil particle that is being filtered is usually the optimum size because this prevents clogging yet holds back soil through a bridging effect [presumably when the sediment builds up against the upstream face of the fabric]. Woven fabric is most commonly used due to its two-dimensional structure, which does not retain silt particles easily.

In contrast, to Martin's emphasis on opening size, Christopher and Holtz (1985) report Wyant's (1980) findings that "a relationship was not apparent between initial fabric permeability or water flow rate and fabric filtering ability", and they conclude that the choice of material is essentially a compromise between particle retention ability and flow rate.

The slurry flow rate through the geotextile must be large enough to ensure that ponding will not exceed the height of the barrier yet small enough to allow a large percentage of the sediment to react to the ponding effect and settle out. A trade-off between filtering efficiency and slurry flow rate must be determined. (Martin, 1985)

According to the Virginia Highway and Transportation Research Council, an ideal silt fence fabric should be robust enough to provide a tear strength of 50 lbs and a tensile reinforcement,

at 20% elongation, of approximately 50 lbs per inch. This, however, also depends on the characteristics of the support fence being utilised. (Martin, 1985)

Ultraviolet stability is important where the silt fence is required for a long period of time (for example a year). To obtain this, it should be ensured that the geotextile purchased has added to it a UV inhibitor. Also, for a required long life usage, the synthetic fabrics polypropylene and polyester are the recommended materials for protection against environmental factors. (Martin, 1985)

There are several design guidelines based on extensive research by the Virginia Department of Transportation. These recommendations are summarised by Richardson and Wyant (1987):

1) The height of the filter fabric silt fence should not exceed 0.9 m (3 ft).
2) The filter fabric should be purchased in a continuous roll and cut to the length of the barrier to avoid the use of joints.
3) Wood or steel posts are set securely on line no more than 3 m apart. Wood posts should be at least 76 mm (3 in.) in diameter and a minimum of 1.5 m (5 ft) long. Metal posts should be T-shaped, weighing more than 2.0 kg/m, measuring no less than 1.5 m (5 ft) long, and having projections for fastening the wire to the fence. (Goldman et al, 1986) state that if no mesh wire is used, the fabric must be of extra-strength and the posts at a maximum spacing of 1.8 m (6 ft)).
4) A trench is excavated 100 mm (4 in.) wide and 100 mm deep along the line of posts and upstream from the barrier.
5) When a wire mesh support fence is used, the wire should be a minimum of 14.5-gage woven wire and must be securely fastened to the upstream side of the posts. The wire should extend flush to the ground.
6) The filter fabric is stapled or wired to the fence with the fabric being allowed to extend to the bottom of the trench.
7) With wooden posts, the wire staples must be No. 9 and at least 38 mm (1.5 in.) long. Where steel posts are used, 17-gage wire is used in lieu of wire staples.
8) The trench is backfilled and the soil compacted over the filter fabric.
9) If a filter fabric silt fence is to be constructed across a ditch line or drainage way, the barrier should be of sufficient length to eliminate end flow and the plan configuration should resemble a horseshoe, with the ends pointing upslope.

When used in a river, 12 mm (0.5 in.) reinforcing bars can be used to hold the bottom of the

fence along the bed of the waterbody. Most silt fences are built in a crescent shape. (Ontario Ministry of Transportation, 1979)

A methodology to determine the height of fence required and the safety factor of a fence built with or without mesh wire is available. (Koerner, 1984)

In many cases, special installation requirements are needed in order to provide additional protection in areas of heavy slurry flow conditions (baffle design or zig-zag design) or concentrated sediment and slurry flow build-up (weirs). When a fence becomes silt laden, tiebacks can be used to provide additional support for the posts. (Martin, 1985)

2.3.2.2 Maintenance of Silt Fences

Although design is very important, the importance of maintenance is often understated and quite often neglected. This is the cause of many such structures' failures. Silt fences require inspection after storms or strong gales which exert enormous stresses on the fence. If any tears or rips are found, they can be patched, but it is recommended to replace the entire fence. When sedimentary deposits reach a depth of 0.5 m (1.5 ft), the silt should be removed or a second silt fence built upstream from the existing one at a suitable distance. (Fluet, 1987)

As a summary on silt fences, Martin (1985) states:

> "When proper silt fence design and installation techniques are utilised, fabric fence structures are able to provide the most cost-effective means available for controlling sheet flow sediment run-off. The silt fence technique is simple, inexpensive, and highly efficient." (Martin, 1985, p. 84)

While Martin (1985) has made a valuable contribution to the literature on silt fences, it should be kept in mind that at the time he wrote the article, he was a "Marketing Development Specialist" with a company which markets geotextiles.

2.3.2.3 Efficiency of Silt Fences

The Virginia Highway and Transportation Research Council has developed a testing procedure for establishing the filtration efficiency of fabric filters. The test procedure is reported by Martin (1985) as follows:

"The filtering efficiency of a fabric can be measured by following the test procedure outlined in VTM-51: 150 grams of minus 10 material of a silty soil are mixed in 50 liters of untreated water and agitated to obtain a uniform mix. This mixture is then dumped down a 48 inch long by 32 inch wide flume elevated to an 8 percent slope. A gutter is attached to the end of the flume. A 39 inch long by 12 inch wide fabric is stretched across the end of the flume opening for the purpose of catching the sediment laden runoff. The flume opening is designed to represent the standard length of a straw bale barrier. The flow of the slurry through the fabric is timed until the water level drops to a given point located behind the fabric. At this point the test is terminated. To measure the filtration efficiency of the fabric a suspended solids sample is taken from the collected filtrate.

The filtration efficiency of the fabric is then calculated by expressing the original suspended solids minus the suspended soils of the filtrate as a percentage of the original suspended solids."

Martin (1985) further relates that the Virginia Highway and Transportation Board has shown that the most realistic particle size that can be filtered and trapped [on a continuous basis] by a silt fence is the silt-size particle. Some clay particles were trapped as a result of a cake developing on the fabric surface but the efficiency of this trapping is not provided. However, it was estimated that the trapping efficiency of **suspended** sediments by straw bales was no more than 20% while silt fences were found to trap up to 75% of the soil.

While these test results appear to heavily favour silt fences over straw bales, the method of testing must be considered. The 914 mm (3 ft) by 305 mm (1 ft) fabric was subjected to only 150 grams of soil. In the field, a silt fence might be subjected to an average flow of 0.03 m^3/s for a period of 15 minutes for a 0.4 ha (1 acre) drainage area during a two year event. This is a volume of 27000 liters, which is 540 times the volume passed through the test fabric. If the area of the fence in the field is 5 times the test fabric, i.e., 2.3 m^2 (25 sq. ft), the flow through the field fabric would be 100 times the flow volume through the test fabric. In addition, a sequence of rainfall events during construction can each add material to the face of the filter fabric, which may cause a gradual loss of flow capacity of the fence. Since the effect of clogging is cumulative, the value of the test procedure in reflecting field conditions has to be questioned.

2.3.3 Filter Fabric on Straw Bales or Piled Brush

In situations where straw bales may not provide adequate protection but may provide the structural component for a check dam, the material with the finer pore spacing will govern the flow rate through the dam. Usually this would be the filter fabric. The design of the check dam

would proceed as if it was a silt fence. Generally a straw bale - filter fabric combination would be used for a low check dam.

2.3.4 Gravel and Earth Berms

Gravel and earth berms are generally not used due to their relatively ineffective filtering efficiencies. Only a large size material 50-75 mm (2 to 3 in.) can be used for the downstream slope where the water exits from the berm. When the berm is located in a steep channel, the downstream toe of the berm tends to fail as the media is carried away by the emerging water. The resulting large pore spaces in the media allow most sediment to pass through the barrier. It is only effective in drainage ditches having a shallow slope and where the sediment is relatively large.

3. LABORATORY TESTING OF SILT BARRIERS

3.1 Need for Further Testing

Previous testing appears to have been directed only towards obtaining efficiency data for the removal of suspended sediments from slurry flows for various barrier materials. Only the suspended load was considered and there is no mention made of the bedload part of the total sediment load. The tests were performed in a batch mode on very small quantities of sediment and water. (Christopher and Holtz, 1985) In the field, runoff volumes and sediment quantities are obviously much larger.

At one location visited as part of this study, the smallest particle size found in the vicinity of a failed straw check dam was 1 mm (0.04 in.). Presumably the smaller particles were washed away. However, substantial amounts of sediments with particle sizes larger than 1 mm (0.04 in.) were deposited in the vicinity, indicating the need to consider the efficiencies of various barrier materials in removing the bedload portion of the total sediment load. It can always be argued that if a silt barrier is capable of retaining a large percentage of the suspended load, it will likely retain all of the bedload. While this is acknowledged, there still remains the question of what is actually attainable in practice.

As discussed earlier, it is not likely that suspended sediments can be removed from a large volume of water with standard silt fences due to cumulative clogging. There thus remains the need for installing barriers which will not clog over time, and as a result fail completely, but remain effective in removing the bedload. To help in understanding the action of more pervious barriers, (i.e. those which will not clog), a series of tests were run at the University of Waterloo Hydraulics Laboratory which more closely resembled conditions at construction sites during a runoff event. Thus, instead of batch tests consisting of relatively small volumes of water and sediment, a continuous flow of sediment-laden water was fed to a flume containing a sediment barrier. The following sections describe the experimental setup and procedures.

3.2 Experimental Setup

An existing flume in the hydraulics laboratory at the University of Waterloo was used for the sediment barrier experiments. The system consisted of a wooden flume, with one side composed of plexiglass, approximately 7 m (23 ft) long, raised on variable metal stands. The water

supply for the pump came from a wooden settling tank composed of removable wooden partitions which allowed the trapping of sediments present in the flume effluent water.

Two separate pumps were used to circulate the water: one driven by the low pressure pump for clean water and the other a jet pump for slurry. Schematic diagrams of the recirculating system are show in Figures 4 and 5. A constant water height was maintained by an outlet near the top of the settling tank.

3.2.1 Barrier Details

Three different types of barriers were tested: straw bale barriers, silt fence fabric (burlap or a geotextile) barriers, and gravel berms.

The straw bales and fabric barriers were supported by a framework permanently attached to the flume. The removable fence was composed of an 18 mm (3/4 in.) frame with dimensions as shown in Figure 6. Geogrid was attached to the upstream side of this frame with the fabric wrapped around the top and two ends and stapled to the frame. For installation, the fence slid between the aluminium frames and the straw bales were wedged in the flume on the upstream side of the geogrid.

A search for suppliers of geotextiles used in silt fences produced a list of companies along with the trade name of the fabric. The companies were contacted and requested to send samples of their product for testing. Table 1 lists the suppliers of the fabrics tested, along with the specifications of their products as per their trade literature.

3.2.2 Flow and Head Measurements

For the clean water flow rates through the fabrics, a U-tube manometer, connected to both sides of the orifice plate in the 75 mm (3in.) PVC pipe, was used to set the different flow rates. The maximum flow rate was measured weighing water accumulated in a wooden box mounted on a scale.

A manometer hose was installed near the fence location in order to determine the water head at the fence under the clean flow rates.

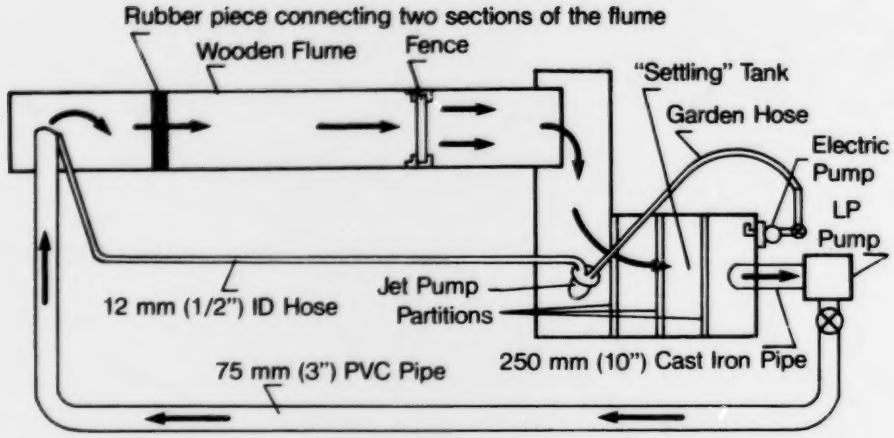


Figure 4 - Plan view of the recirculating system

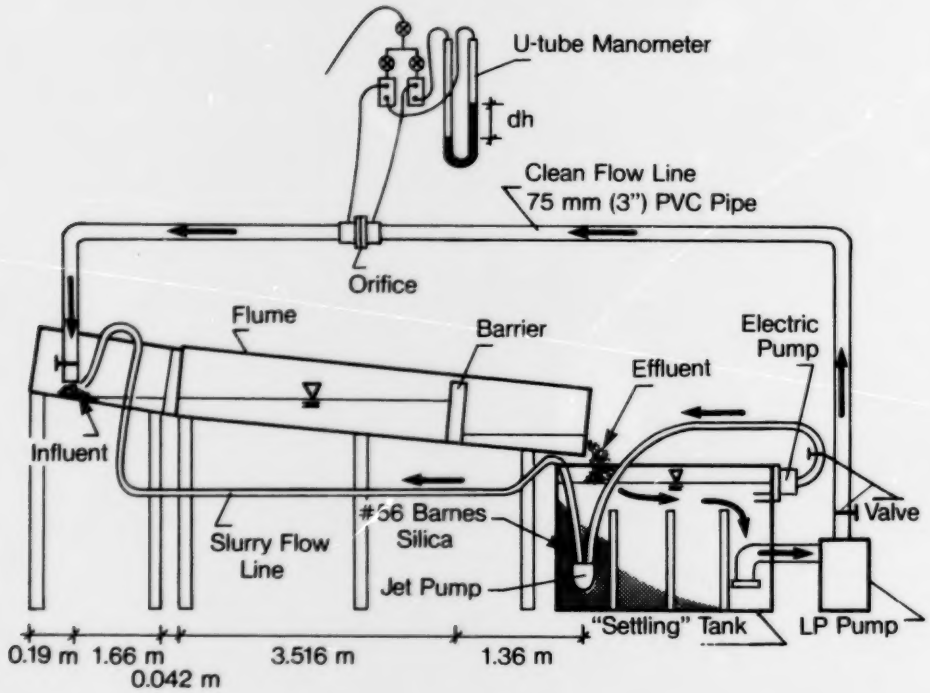


Figure 5 - Side view of the recirculating system

3.2.3 Sediment and Water Profile Measurements

The sediment accumulation in front of the silt barrier was measured using a point gage mounted on a carriage which slid along the top of the flume on aluminium angle rails. Readings were taken along the centre of the flume, although at times when the water was murky (i.e. when straw bales were used), readings were taken near the plexiglass side.

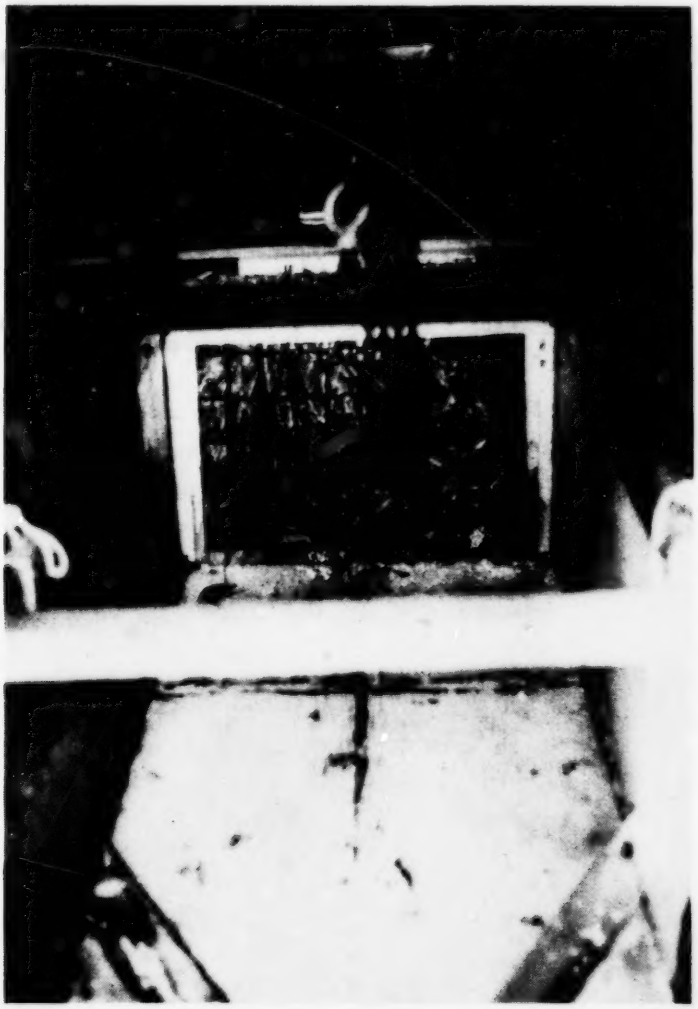


Figure 6 - Barrier support looking upstream

3.2.4 Sediment Concentration Measurements

The inflow and outflow were sampled using 250 ml and 1000 ml graduated cylinders respectively. The samples were then filtered to determine the solids concentrations in the influent/effluent samples. It involved the use of a vacuum which forced water through a laboratory filter (type AP40-047-05 from Millipore Ltd) which captured the suspended solids. The dry sample was then weighed and the concentration calculated.

3.2.5 Sediment Media

The sediment used in these experiments was #56 Barnes silica sand. The average particle size is 0.2 mm (0.008 in.) and is classified as a medium sand. This sand size is a practical size for the type of experiment possible in the University of Waterloo hydraulics laboratory with the equipment available from previous research. It was also felt that this size is a reasonable field value of particle sizes transported due to runoff water, although a variety of sand sizes should ultimately be tested. Figure 7 is the grain size distribution curve for the sand used in the experiments.

Obviously, it would be useful to extend the testing to include a range of sediment sizes, for example from a medium to coarse silt to a coarse sand. However, since each test takes two or three days, including setup time, such a test programme could not be undertaken during the present study period.

Table 1 - Properties of fabrics (as per trade literature)

COMPANY	FABRIC NAME	PHYSICAL PROPERTIES					HYD. PROP.		MECHANICAL PROPERTIES					
		Mass (oz/sq.yd)	Thickness (mils)	EOS (AOS) (US Stand. Sieve)	Open Area (%)	UV Res. (%)	Permeab. (cm/s)	Flow Rate (gal/ft^2/ min)	Elong. (%)	Puncture Strength (lbs)	Mullen Burst (psi)	Grab Tensile (lbs)	Abrasion Resist. (lbs)	Trapezoid Tear Str. (lbs)
		TEST PROCEDURE												
		ASTM D-3776	ASTM D-1777	Corps of Engineers	CWO 22125-86	ASTM D-4355	ASTM D-4491	ASTM D-4491	ASTM D-1682	ASTM D-751	ASTM D-3786	ASTM D-1682	ASTM D-3884	ASTM D-4533
Carthage Mills	FX-11	3	10	20-40 $	1		0.01		22	75	290 *	130		90 **
	FX-300C	7	19	70 $	5-6		0.003		25-30	140	530 *	390/280	120/90	90/60 **
	Poly FX	5.4	13	40-60 $	10-15	90	0.037		25 ####	150 ####	550	325	100	100
Terrafix	Terrafix 270R	8.0	3	150-270 $			0.26		70-100		247 *	125		
	370RS	13.9	4	150-270 $			0.18		70-100		392 *	225		
	Terratrack 24-11	3.1	0.51	50 $			0.0052		27		300 *	157		
Exxon	100S			50-70 #		90 ##	0.1	0.3 ###	20 ####		250	100 ####		50 ***
Terratex	SC	2.5	12	20-40		High	0.008		21		300 *	120		130 **
American Excelsior	SF26	3	6	40/100		90					350	150WARP /90FILL		
	Burlap	6.35												

ASTM.03.81.08 (proposed), ## FEDTM 191, $ CW 02215,NOV '77, ### VTM 51 79, #### ASTM D-4632, *** ASTM D-1117, **ASTM D-2263, * ASTM D-751

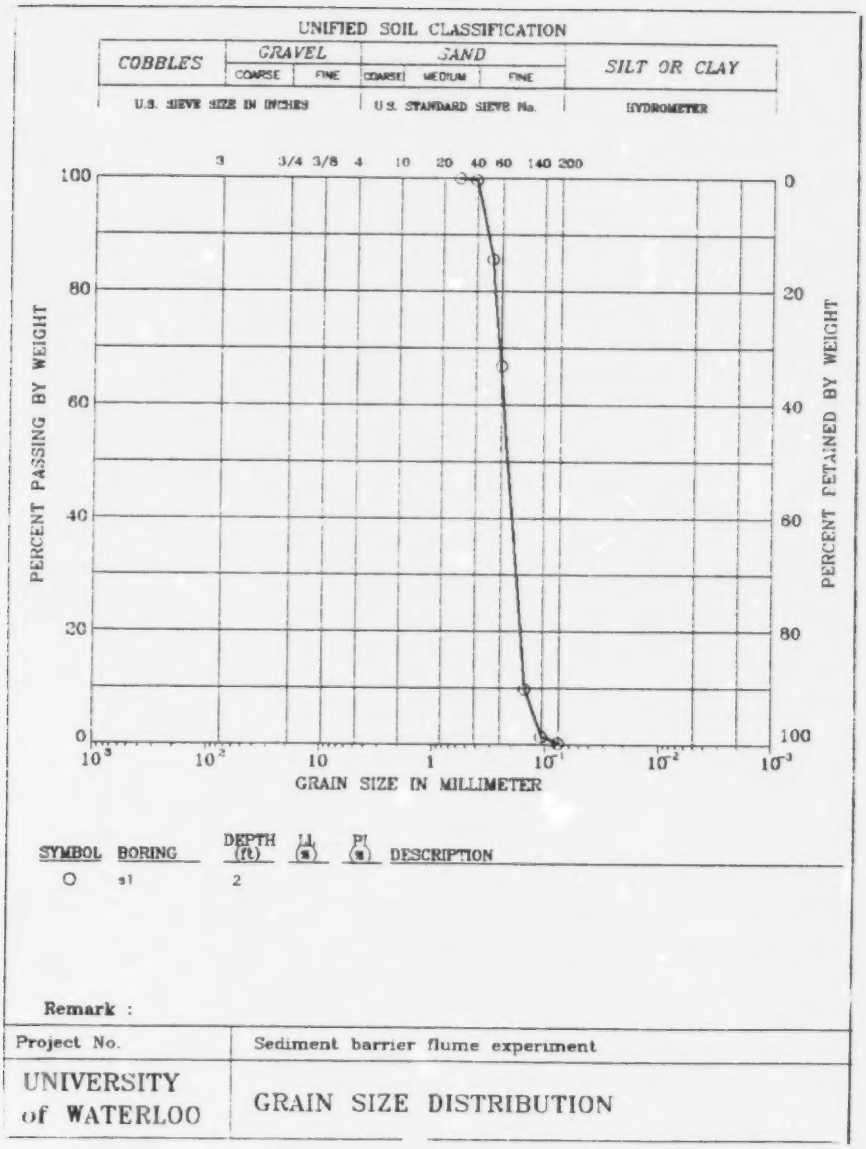


Figure 7 - Grain size distribution for the silica sand

3.3 Experimental Procedures

Two types of experiments were conducted - clean flow and slurry flow. Clean flow tests determined the water head at various flow rates, and also the maximum flow rate at 380 mm (15 in.) head. The slurry flows were to obtain the filtration efficiency, sediment profiles, and head at barrier with respect to time.

The first series of experiments (nos. 1 through 14) were conducted to determine the maximum flow rates of the available fabrics (burlap, straw bales, and geotextiles). The flow was set so that the water depth upstream from the barrier was 380 mm (15 in.). This left 75 mm (3 in.) of freeboard in the flume.

Filtration efficiency simply compares the influent/effluent SS concentrations to determine the percentage of sediment retained by the specific application. It is based on a comparison of weighed samples of solids in the influent and effluent water.

Sediment accumulation readings were taken periodically while the sediment was accumulating upstream from the sediment barrier at 0.5 meter intervals.

3.4 Experimental Results

Table 2 is a chronological list of the experimental programme. While all filter samples were tested for permeability, only three fabrics were tested with the slurry flows. These were the fabrics having the intermediate values for permeability. The fine materials clogged almost immediately, while the coarse materials did not provide adequate water storage. The materials which were tested were those providing sufficient storage without undue clogging. Time constraint prevented testing all samples with slurry flow.

3.4.1 Clean Water Flow Rates

The maximum depth possible in the flume is approximately 380 mm (15 in.). A series of tests were performed to determine the relative flow capacities of the various filter materials obtained from various suppliers. Figure 8 shows the flow rates for this maximum attainable depth in graphical form. These plots are in units of l/s per m^2 (i.e. flow rate per unit area). While these tests do not conform to any particular permeability standard, the results do clearly indicate the relative permeability of the various materials tested.

Table 2 - List of experiments in chronological order

Exp. No.	Fig. No.	Fabric Type	Flow Rate l/s	Type of Flow	Purpose of Experiment
1	9a	Burlap		Clean	permeability test
2		FX-11		Clean	permeability test
3	9b	270R		Clean	permeability test
4		24-11		Clean	permeability test
5	9c	100S		Clean	permeability test
6	9d	370RS		Clean	permeability test
7		SC		Clean	permeability test
8		SF26		Clean	permeability test
9	9e	FX-300C		Clean	permeability test
10		Poly FX		Clean	permeability test
11		Horiz.Bale		Clean	permeability test
12		Horiz.Bale		Clean	permeability test
13		Horiz.Bale		Clean	permeability test
14		Horiz.Bale		Clean	permeability test
15		None	10.84	Slurry	background influent SS conc.
16		Burlap	10.94	Slurry	Filtration Efficiency (F.E.)
17		24-11	10.78	Slurry	F.E.
18	10a,11	Burlap	2.05	Slurry	Sediment Accumulation (S.A) Water Head at Fence (W.H.), and F.E.
19		None	2.20	Slurry	slurry flow via jet pump
20	10b,12	Horiz.Bale	0.79	Slurry	F.E. S.A., W.H.
21	10c,13	Horiz.Bale	0.81	Slurry	F.E., S.A., W.H., angle effects on effl. sampling
22		None	0.98	Slurry	test in/effluent sampling
24		Vert.Bale		Clean	max. clean flow of bale on its side (larger area at bale/water face)
25	10d,14	Vert.Bale	1.33	Slurry	F.E., S.A., W.H., bale on side
25-2		Vert.Bale	1.08	Slurry	F.E., S.A.,W.H.,lower flow
25-3		Vert.Bale	1.24	Slurry	F.E., S.A., W.H., same exp.
26		None		Slurry	slurry flow & conc. thru jet
27	10e,15	FX-300C	1.42	Slurry	F.E., S.A., W.H.
28	16	Vert.Bale	1.68	Slurry	F.E., S.A., W.H.
29	10f,17	Vert.Bale	3.45	Slurry	F.E., S.A., W.H., flow > #28
30	18	Vert.Bale	4.25	Slurry	F.E., S.A., W.H., flow > #29
31	19	370RS	1.99	Slurry	F.E., S.A., W.H.
32	10g,20	100S	1.42	Slurry	F.E., S.A., W.H.
33	9f,10h,21	Horiz.Bale	1.51	Slurry	F.E.,S.A.,W.H.,permeability
34	9g,22	Grav. Berm	2.21	Slurry	F.E.,S.A.,W.H.,permeability
35		None		Slurry	jet pump slurry flow rate
36	9h,10i,23	Rock Berm	4.03	Slurry	F.E.,S.A.,W.H.,permeability slope = 10%
37	10j,24	Rock Berm	4.03	Slurry	F.E.,S.A.,W.H., slope=4%
38	10k,25	Rock Berm	4.03	Slurry	F.E.,S.A.,W.H., slope=1%

Several exceptions exist where a water depth at the fence of 380 mm (15 in.) could not be attained due to the high permeability of the barrier material, as was the case with the burlap and the gravel berms. Also, the water head at the bales varied depending on their geometry. Four straw bale experiments (numbered 25, 28, 29 & 30) had the bales placed with the stalks vertically while the other three bales were placed in the flume with the stalks horizontally.

Rating curves (clean flow rate versus head at the barrier) are given in Figures 9a through 9h for various materials tested. The theoretical line was plotted using Supercalc 5™ regression analysis of the experimental data points. These diagrams indicate clearly that there is an initial water head required before flow is initiated through a material, the head depending on the permeability of the barrier material. This initial head also indicates the initial pond size that the barrier will create, regardless of the flow.

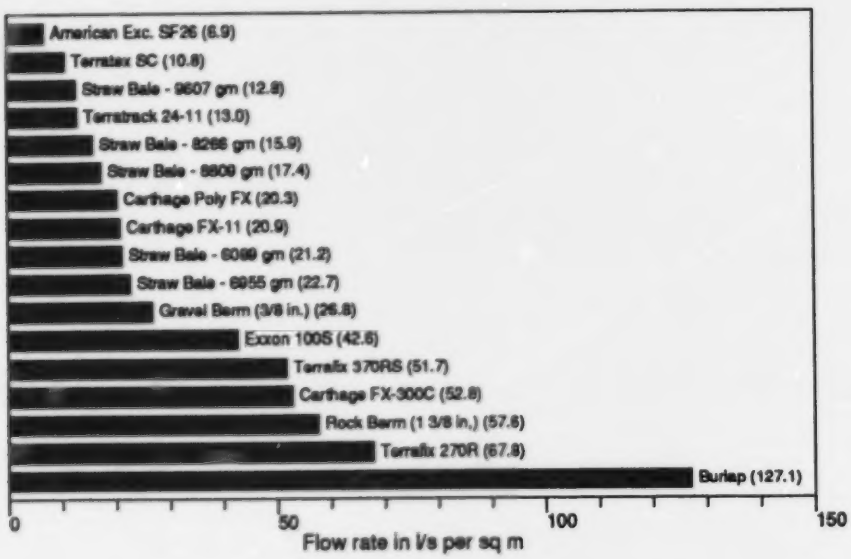
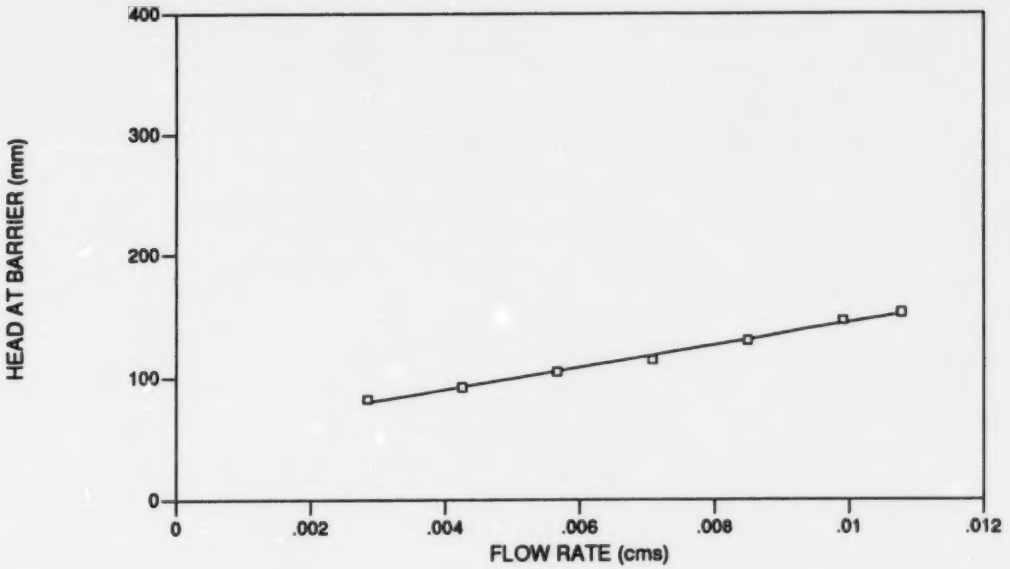


Figure 8 - Clean water flow rates at 380 mm (15 in.) depth
(note exceptions in text)

a) Burlap



b) Terrafix 270R

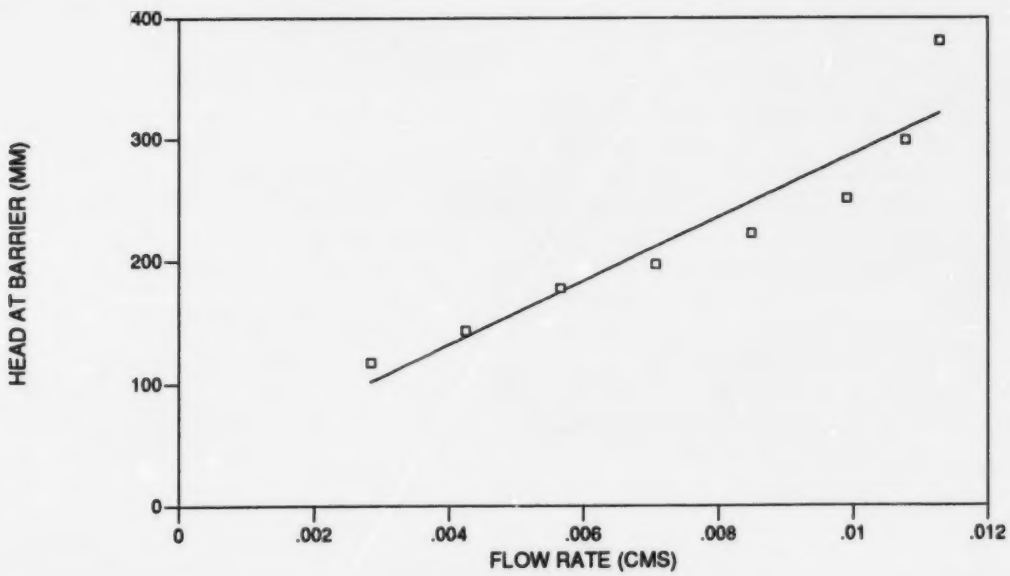
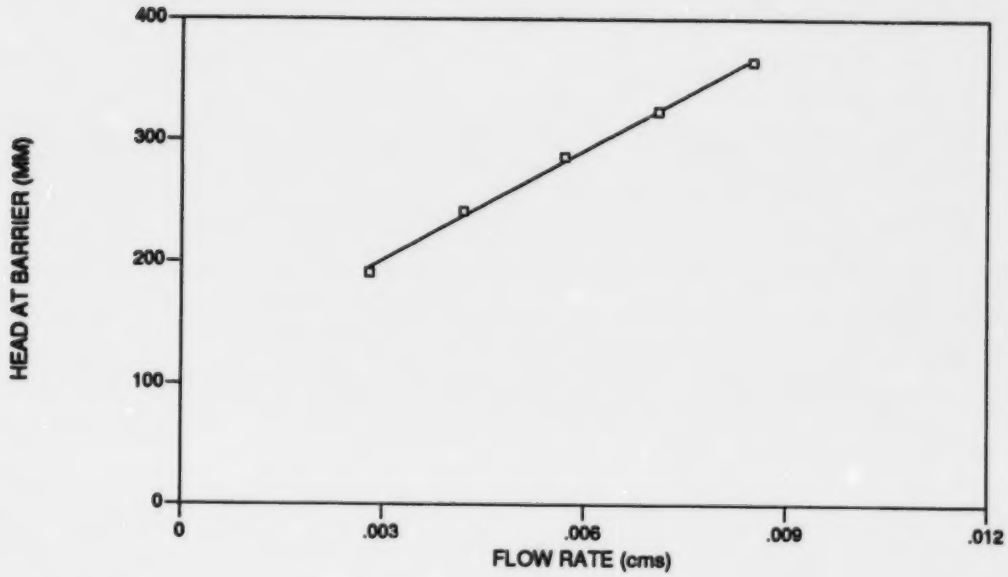


Figure 9 - Barrier rating curves

c) Exxon 100S



d) Terrafix 370RS

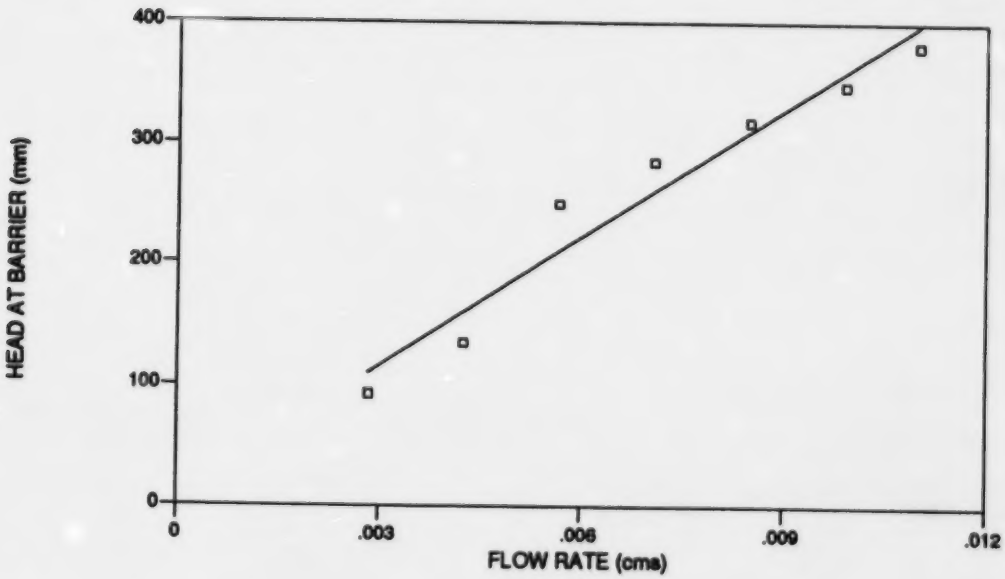
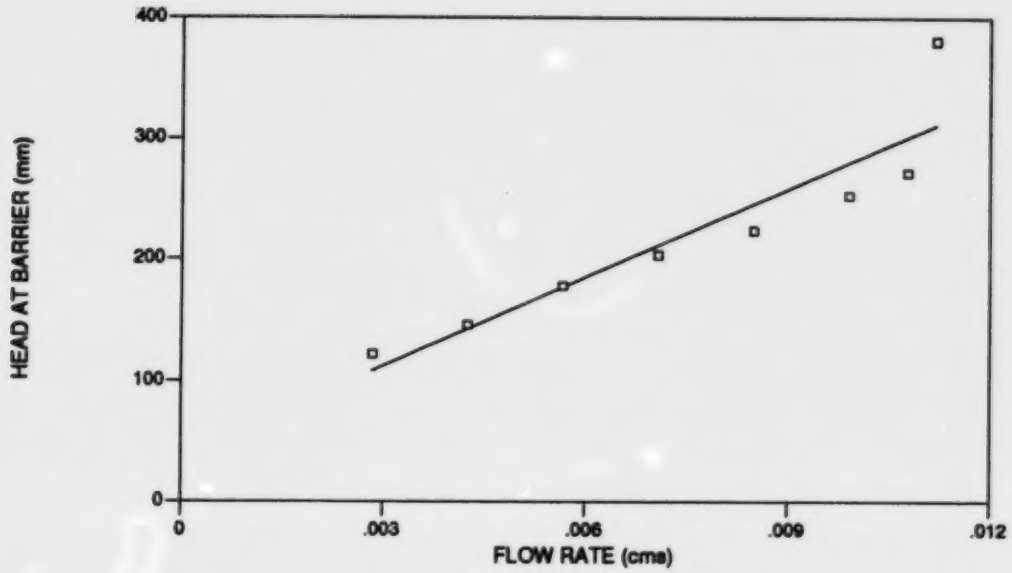


Figure 9 - Barrier rating curves (Cont'd.)

e) Carthage FX300C



f) horizontal straw bale

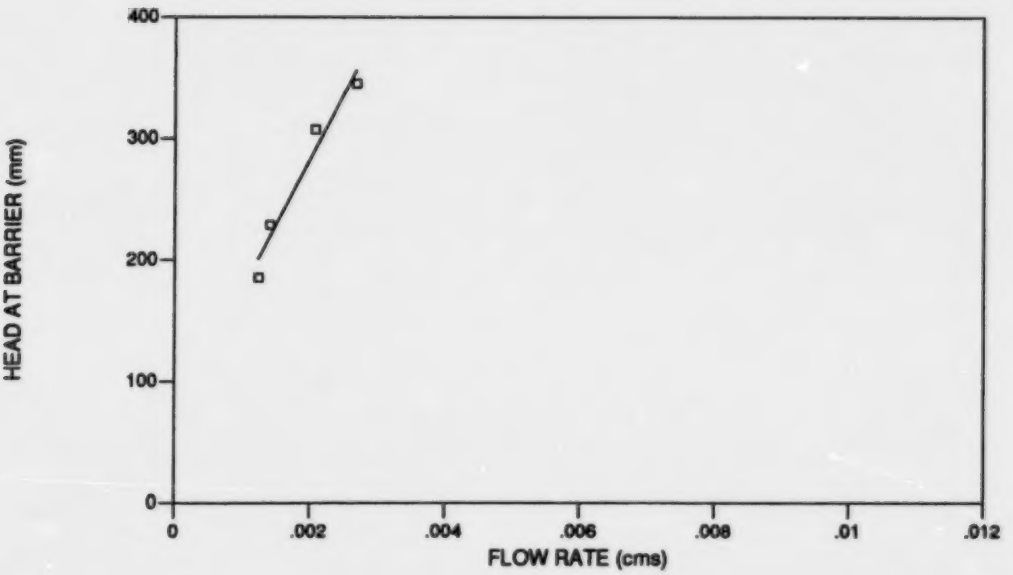
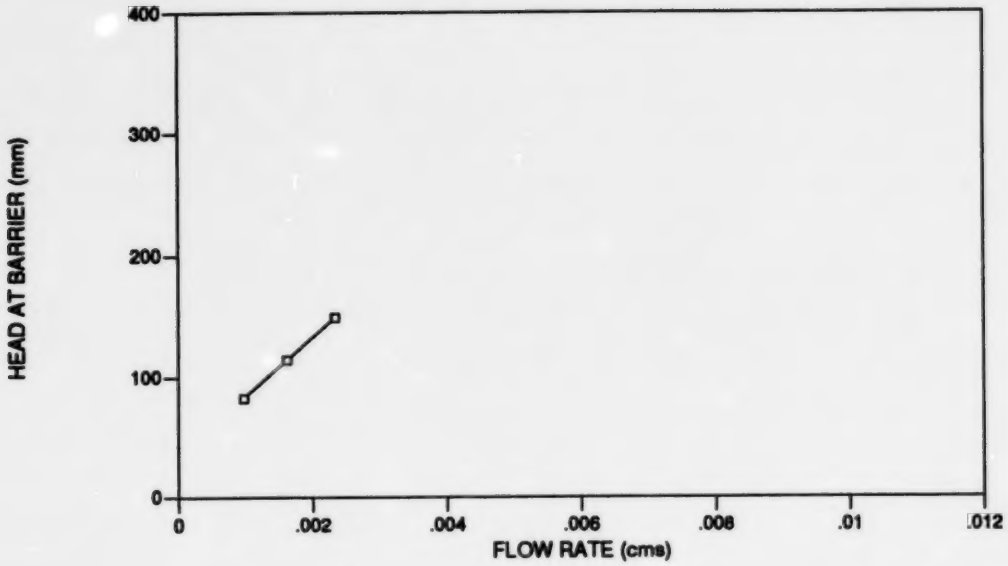


Figure 9 - Barrier rating curves (Cont'd.)

g) Pea gravel berm



h) 50 mm (2 in.) crushed rock berm 10%

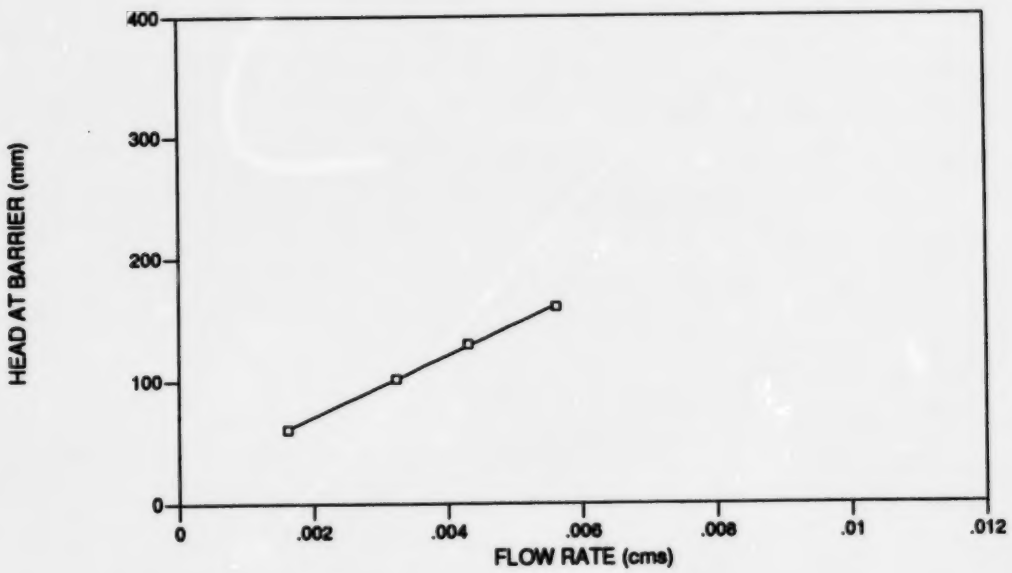


Figure 9 - Barrier rating curves (Cont'd.)

3.4.2 Filtration Efficiency

The main purpose of these experiments was to study and compare the filtration efficiencies of typical barrier materials, especially straw bales.

The slurry flow for all the experiments was approximately 0.45 l/s (0.016 cfs). The average SS concentration in the slurry flow system was approximately 140 gm/l. The actual influent sediment concentration depends on the total flow rate produced from both pumps.

The clean flow rates were conducted to determine the maximum flow rate for that particular barrier material being tested. The flow rate used in the slurry run was usually set to one-half this maximum clean flow, or at least, well below the maximum flow to ensure the barrier would not overtop due to clogging.

Figures 10a through 10k are plots of the water depth upstream of the barrier for some of the slurry flow experiments. The initial depth results from passing the flow through a clean filter. With time, the depth at the fence usually increases at a linear rate, indicating a specific rate of clogging. The plots in Figure 10 can only be used to compare the materials clogging rate for the 0.2 mm (0.008 in.) sand used in the experiments. These rates would vary depending on the sediment characteristics in a particular situation.

Figures 11 through 25 shows the sediment trapping efficiency of the barrier as a function of time (a) and the profiles of the sediment deposited upstream from the barrier (b). Generally, the efficiency was high when the sediment first accumulates at the upstream end of the flume, where the water velocity was first reduced due to ponding. As the space in front of the barrier became filled, more sediment reached the barrier and some of it passed through, thus reducing the efficiency. For burlap, the efficiency was quite variable with time as intermittently, slugs of sediment would erode from the accumulated sediment due to small variations in the water level in front of the barrier.

Figures 26 and 27 are plots of the efficiency as a function of the depth of sediment accumulation against the upstream face of the barrier for the straw bale and fabric/gravel experiments, respectively. A comparison of these figures show that straw bales remain more efficient as the sediment basin fills up. The straw bale efficiency remains high, in the order of 95% until all the storage is filled. The fabric and gravel barriers lose their trapping capabilities when the sediment reaches a depth of 1/2 of the barrier height. For the gravel berm, the plot shows the

sediment trapping capacity is related to the channel slope: the smaller the slope, the better the trapping efficiency.

Figure 26 shows clearly the effect of having a tight fit of the straw bale in the flume. The bale marked as "loose" was only about 70% efficient whereas the bales either weighted down or clamped were over 95% efficient. This illustrates the importance of properly staking, packing, and digging in the straw bale in field applications.

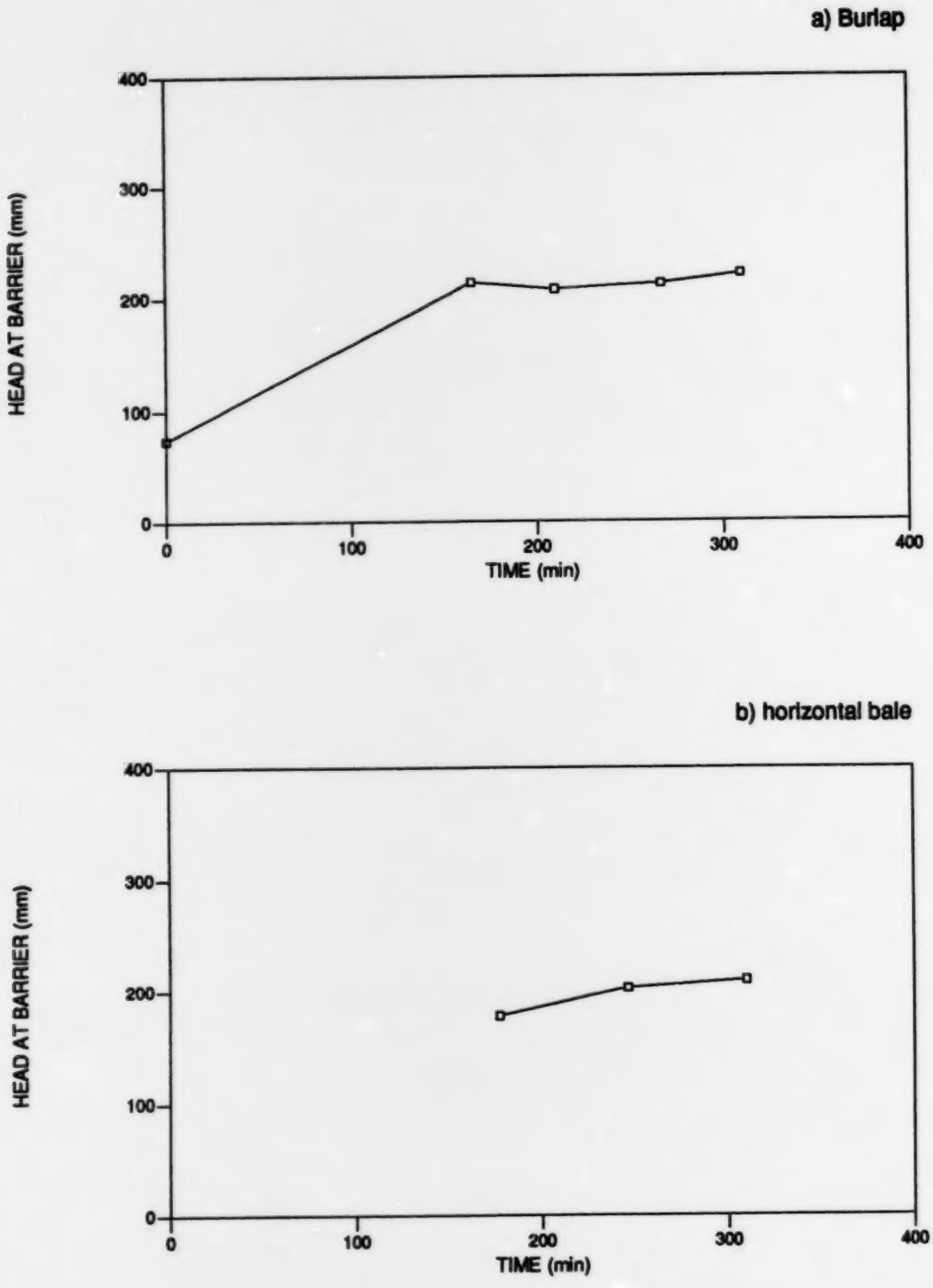
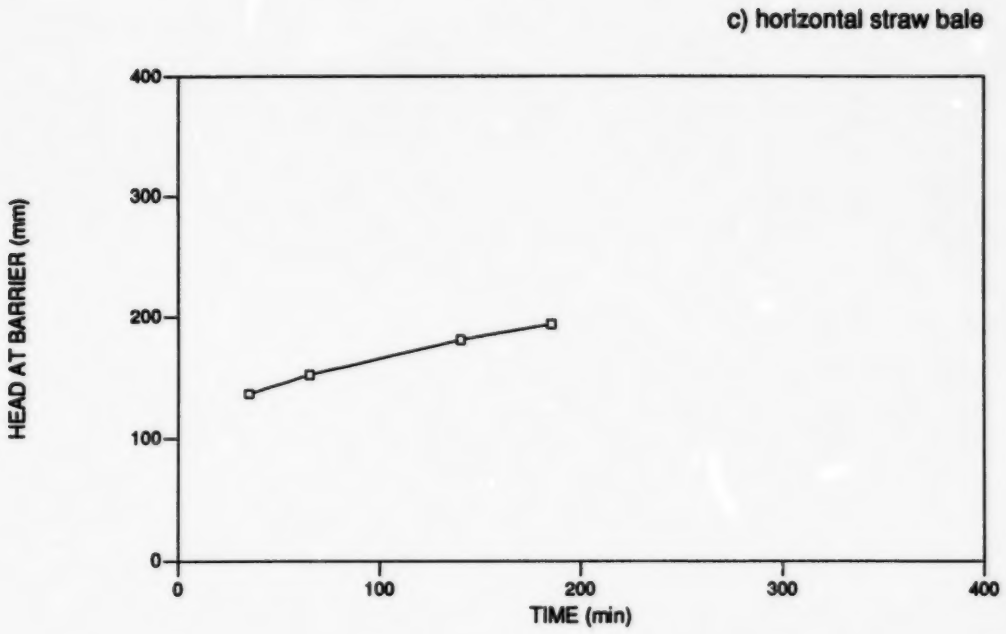


Figure 10 - Water depth @ barrier versus time with slurry flow



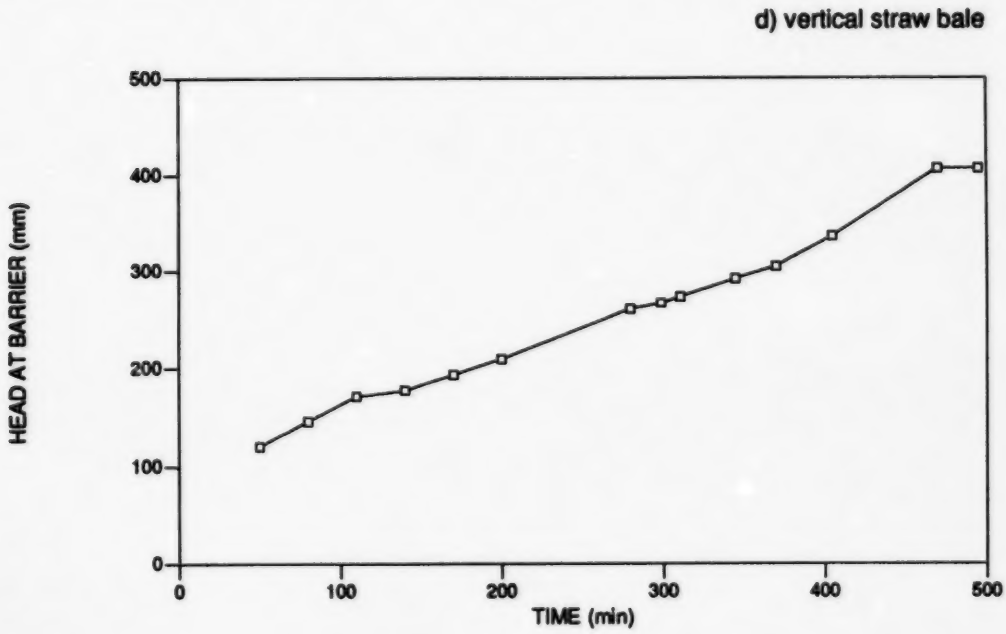
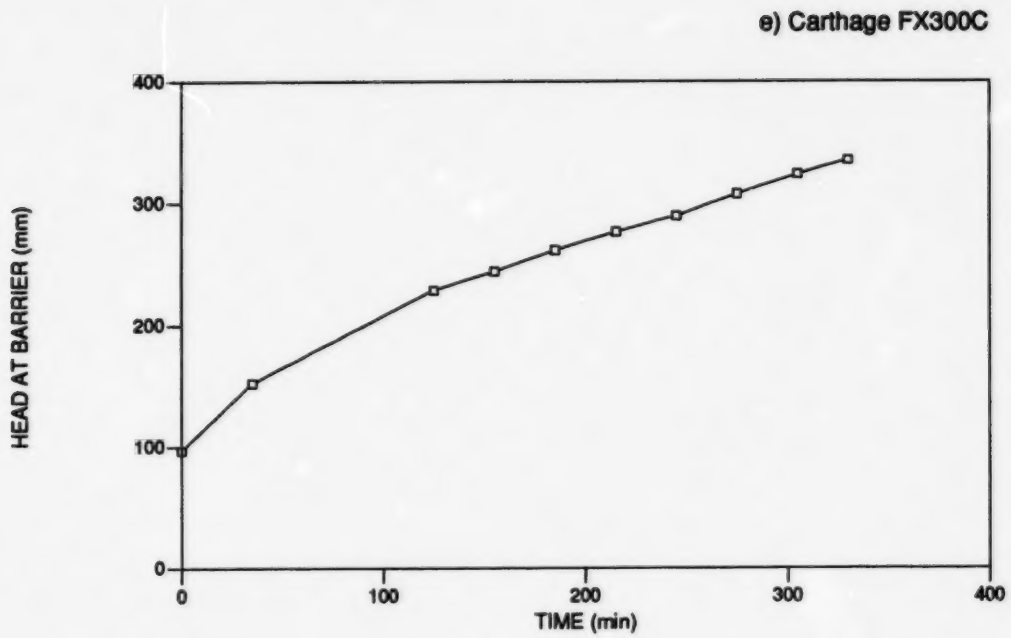


Figure 10 - Water depth @ barrier versus time with slurry flow (Cont'd)



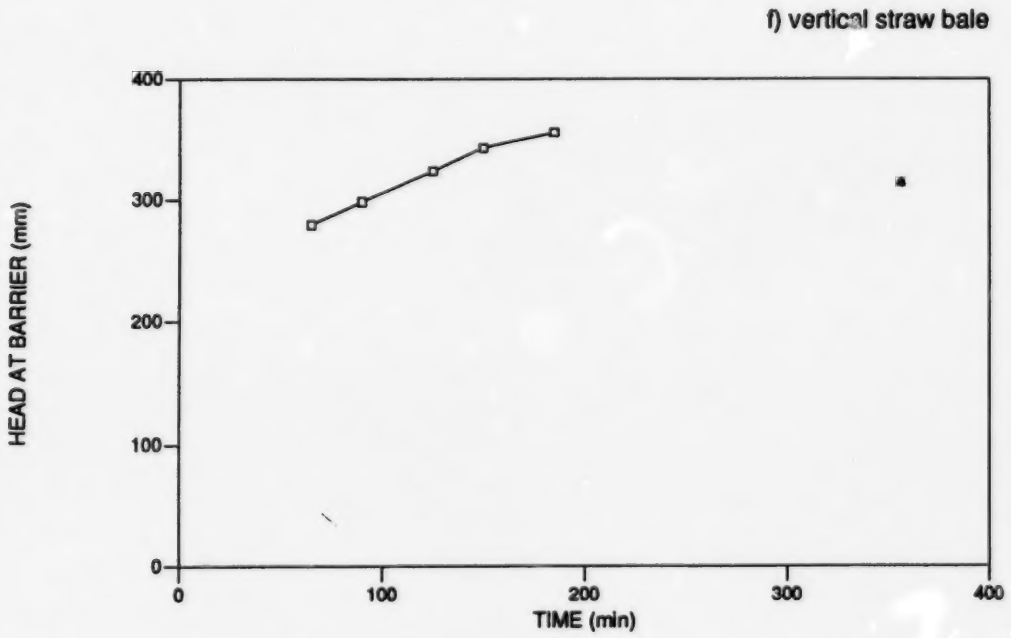
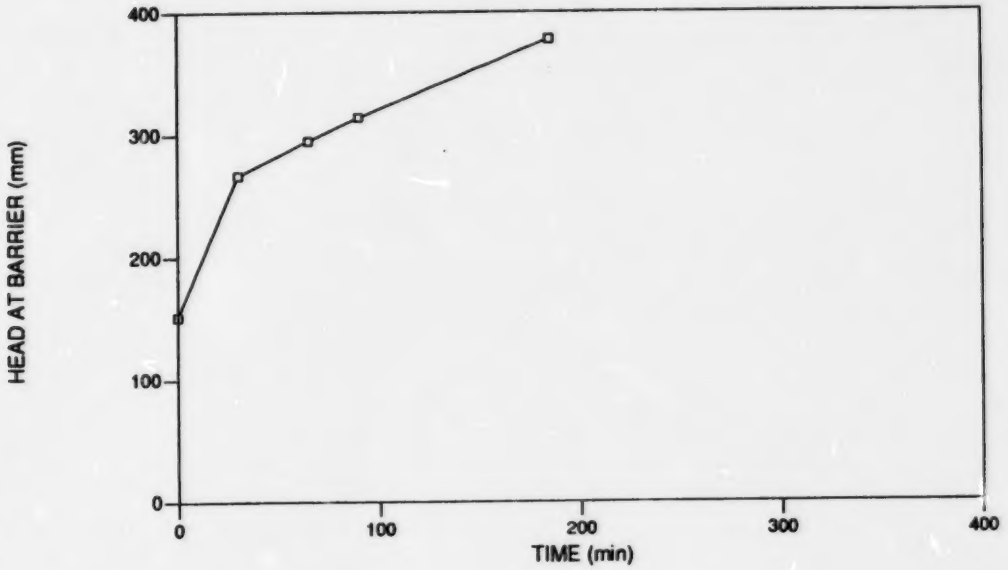


Figure 10 - Water depth @ barrier versus time with slurry flow (Cont'd)

g) Exxon 100S



h) horizontal straw bale

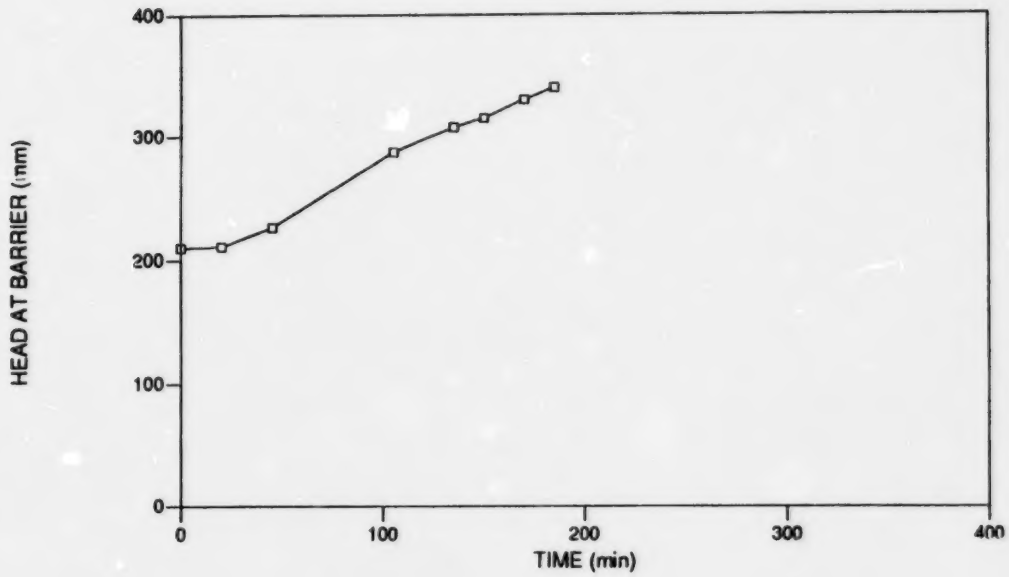
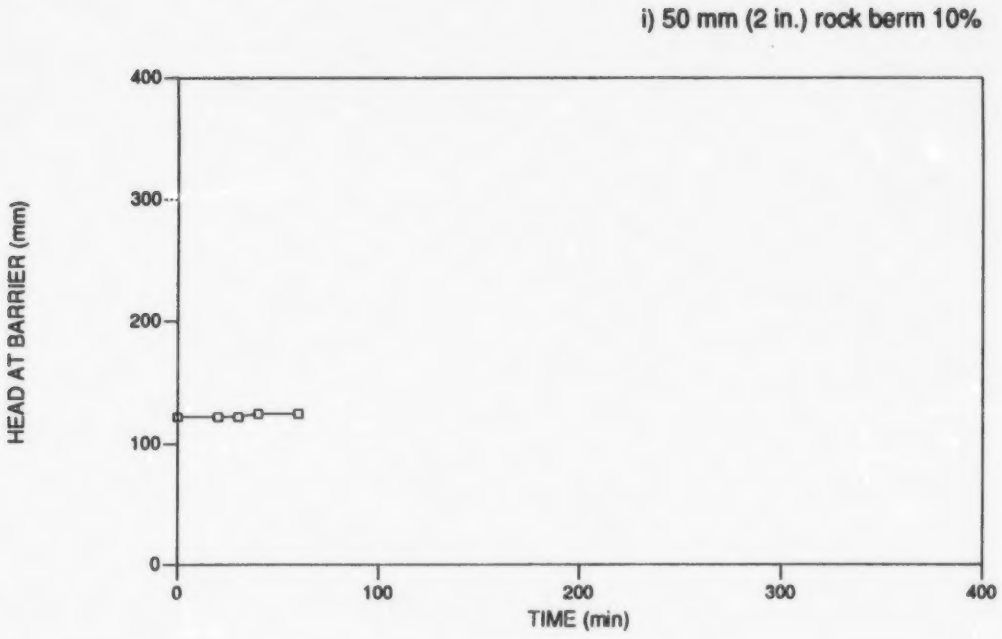


Figure 10 - Water depth @ barrier versus time with slurry flow (Cont'd)



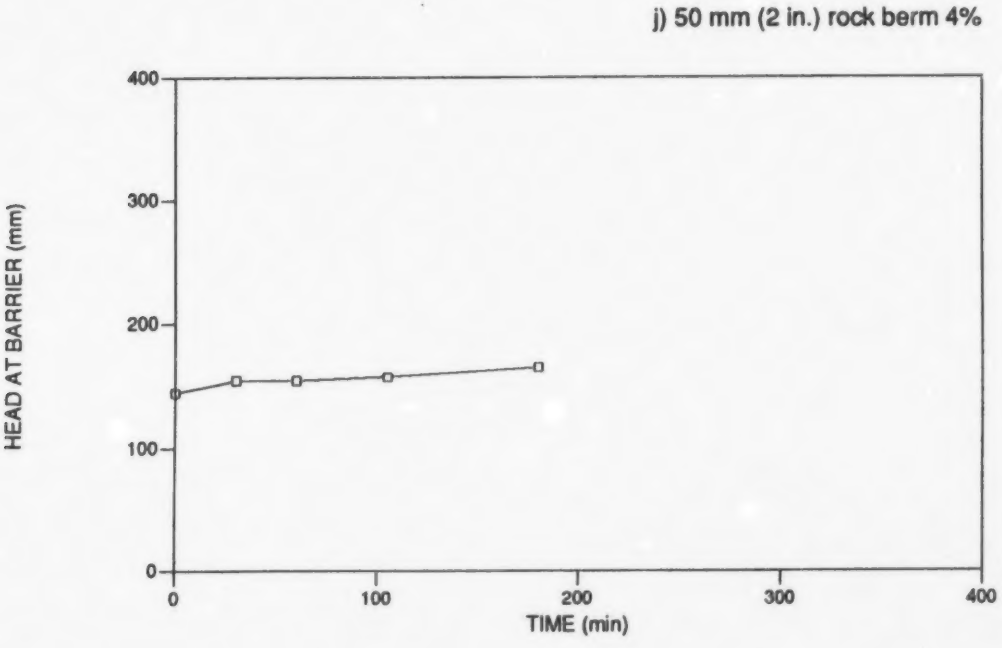


Figure 10 - Water depth @ barrier versus time with slurry flow (Cont'd)

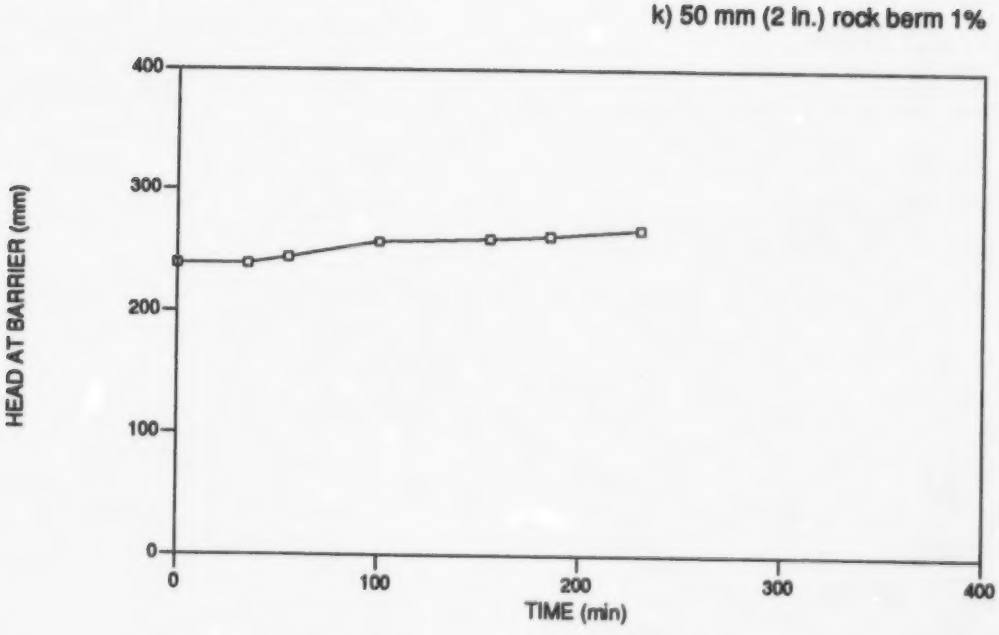
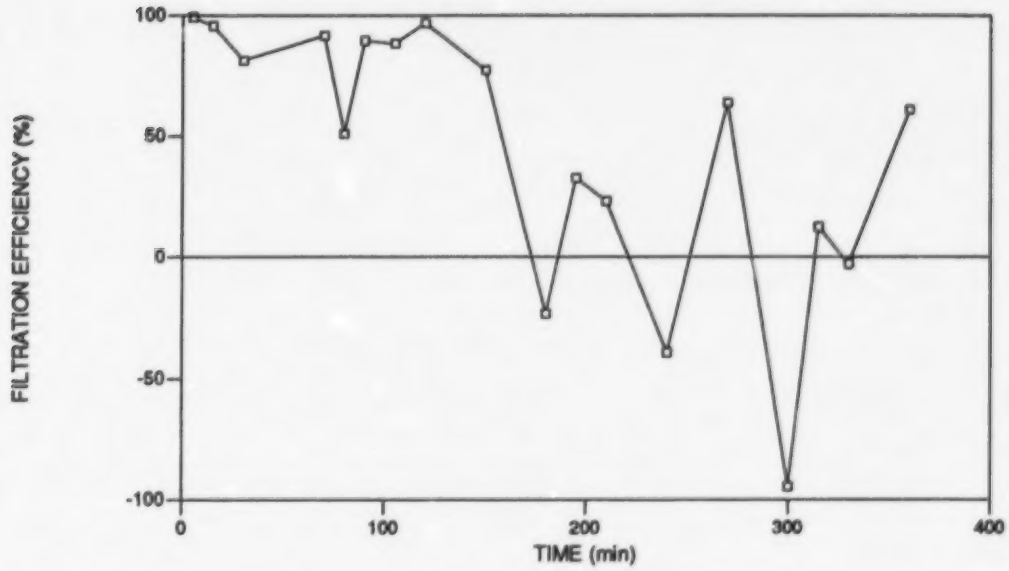


Figure 10 - Water depth @ barrier versus time with slurry flow (Cont'd)



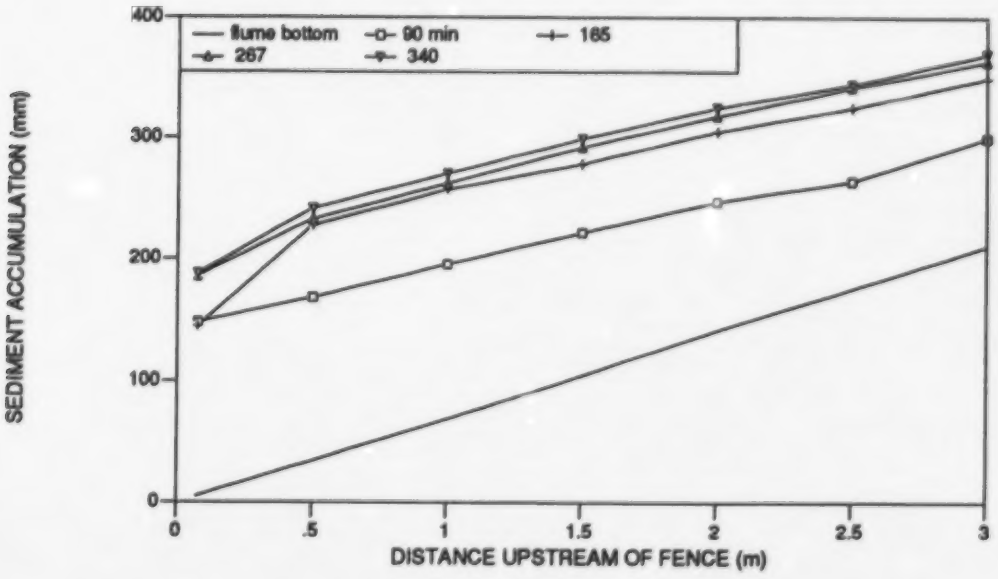
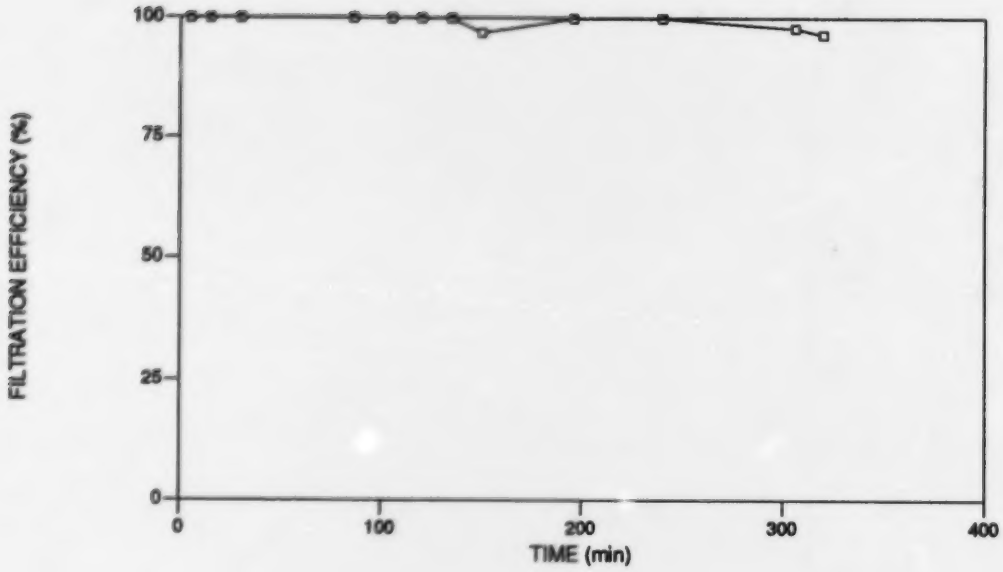


Figure 11 - Filtration efficiency and sediment profiles - Burlap



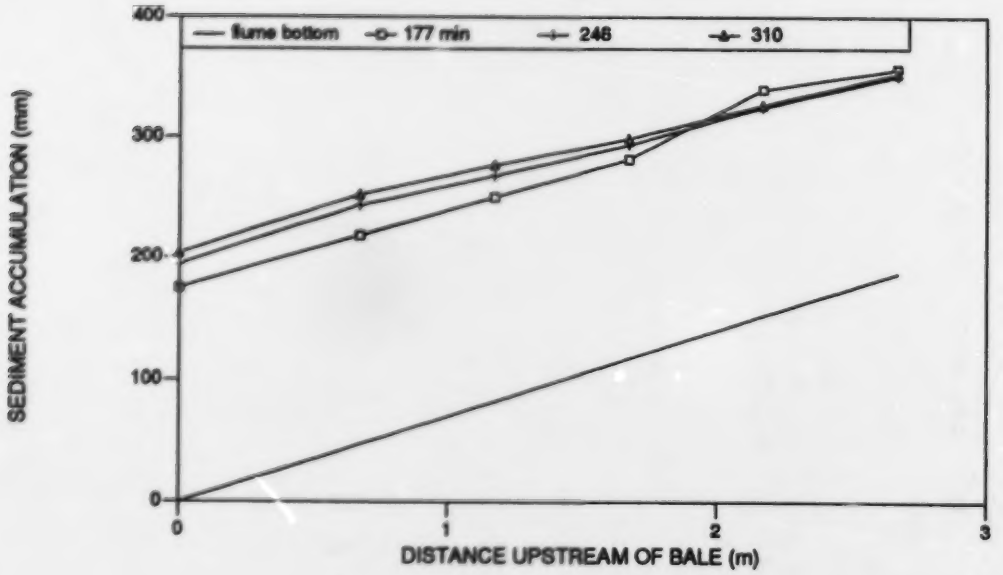
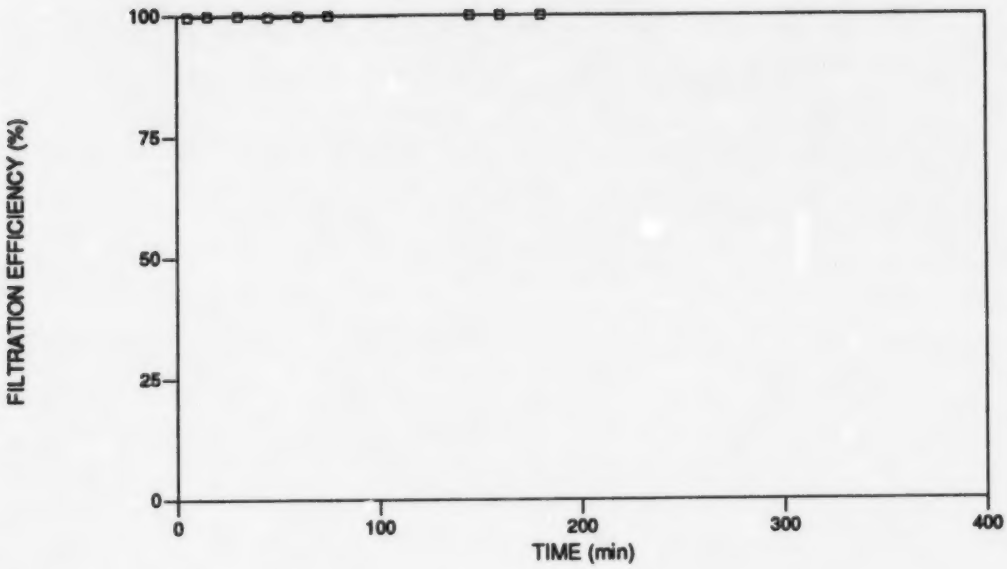


Figure 12 - Filtration efficiency and sediment profiles - Straw/hor.



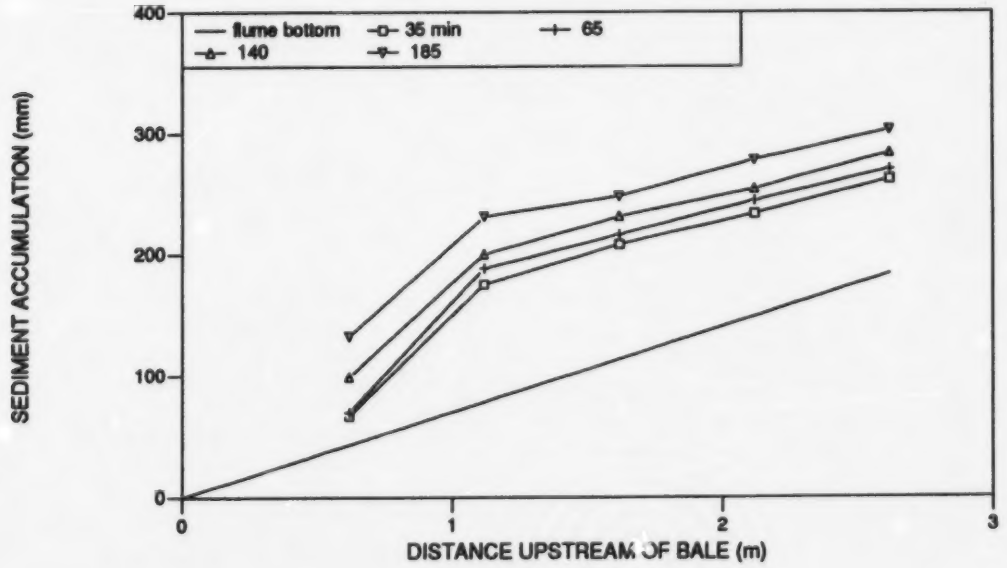
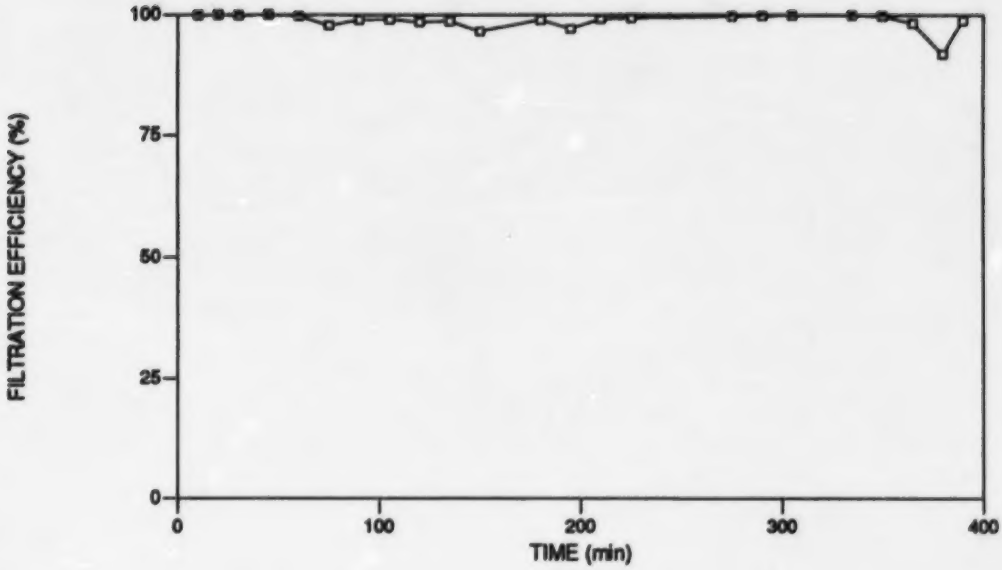


Figure 13 - Filtration efficiency and sediment profiles - Straw/hor.



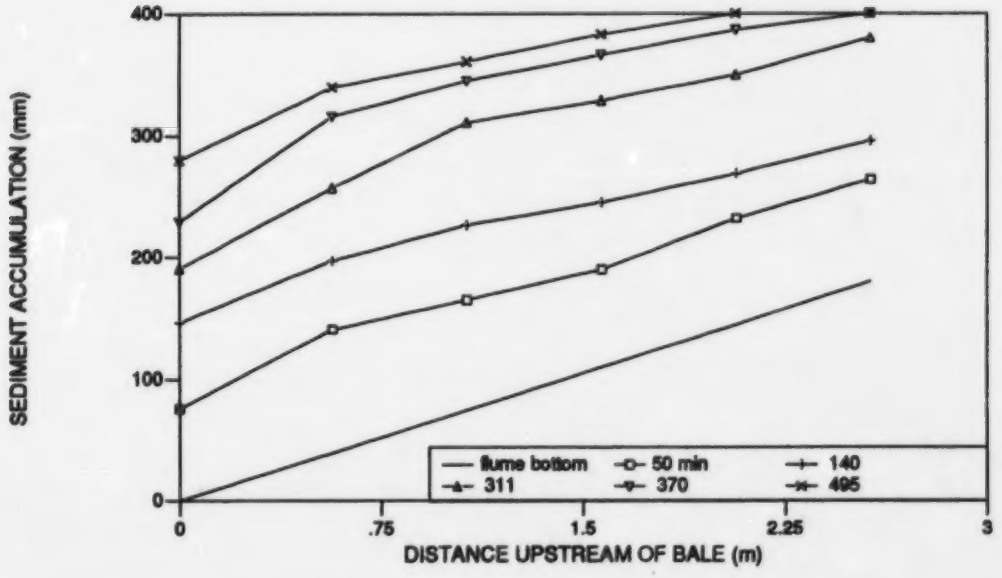


Figure 14 - Filtration efficiency and sediment profiles - Straw/vert.

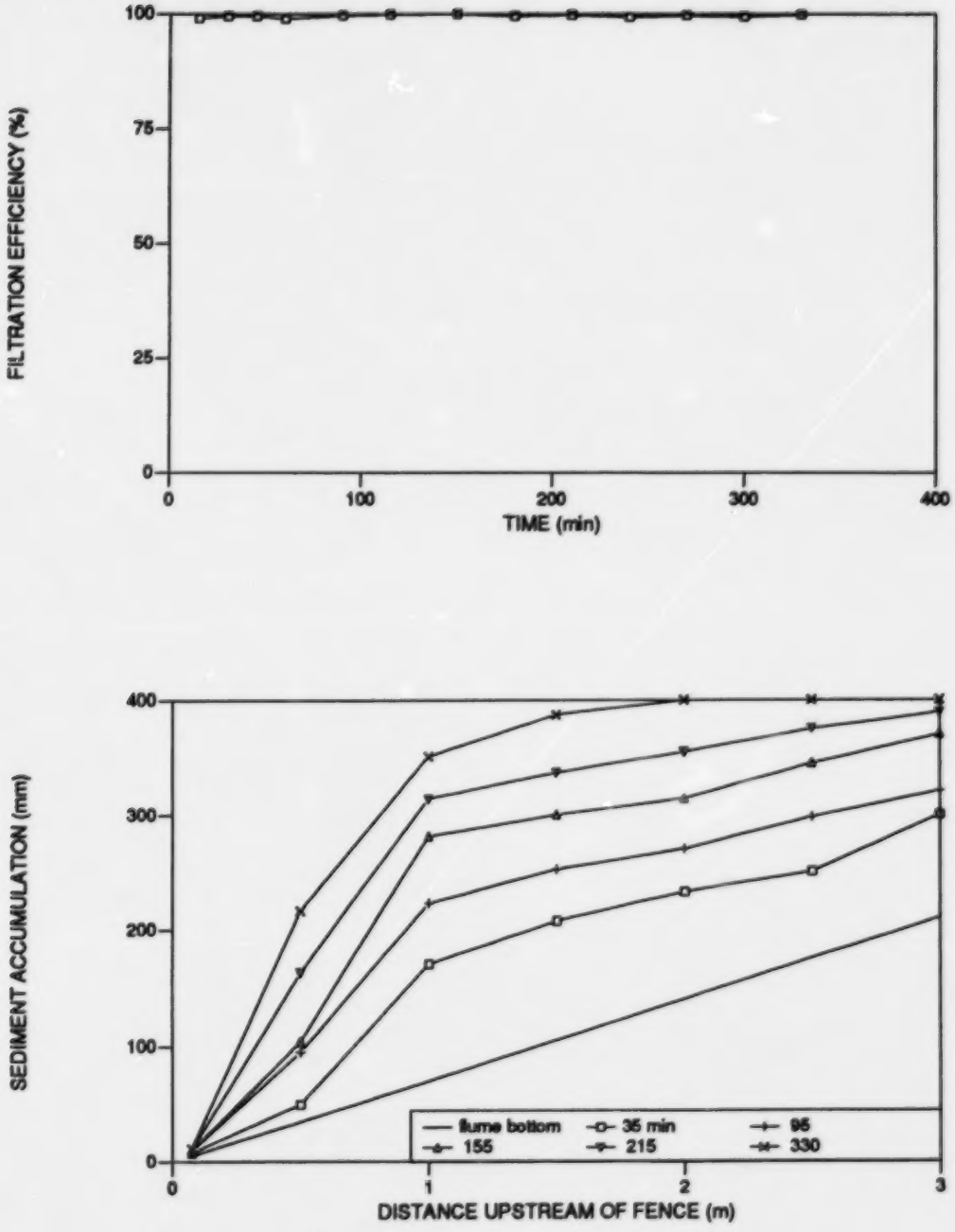


Figure 15 - Filtration efficiency and sediment profiles - Carthage FX300C

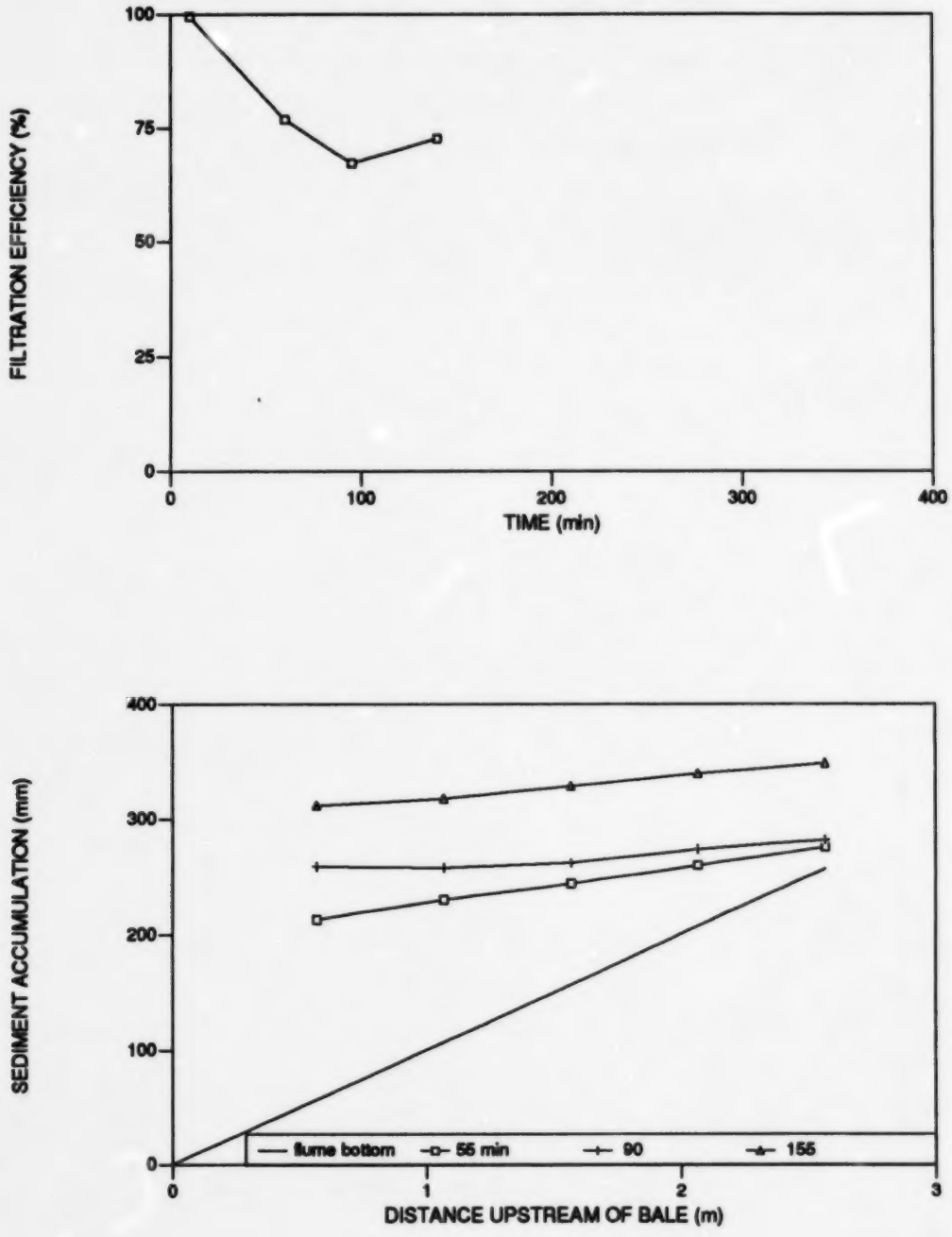
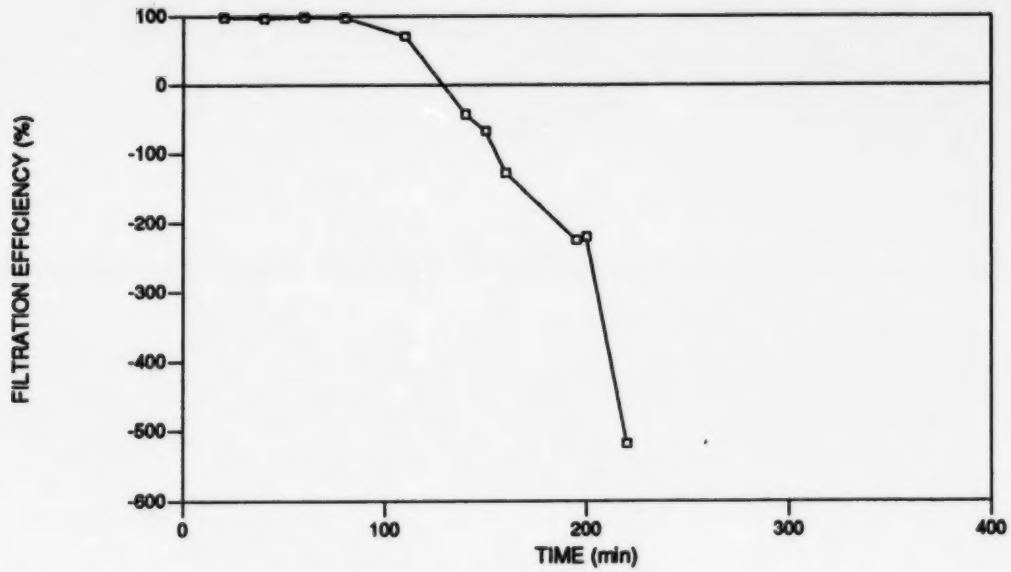


Figure 16 - Filtration efficiency and sediment profiles - Straw/vert.



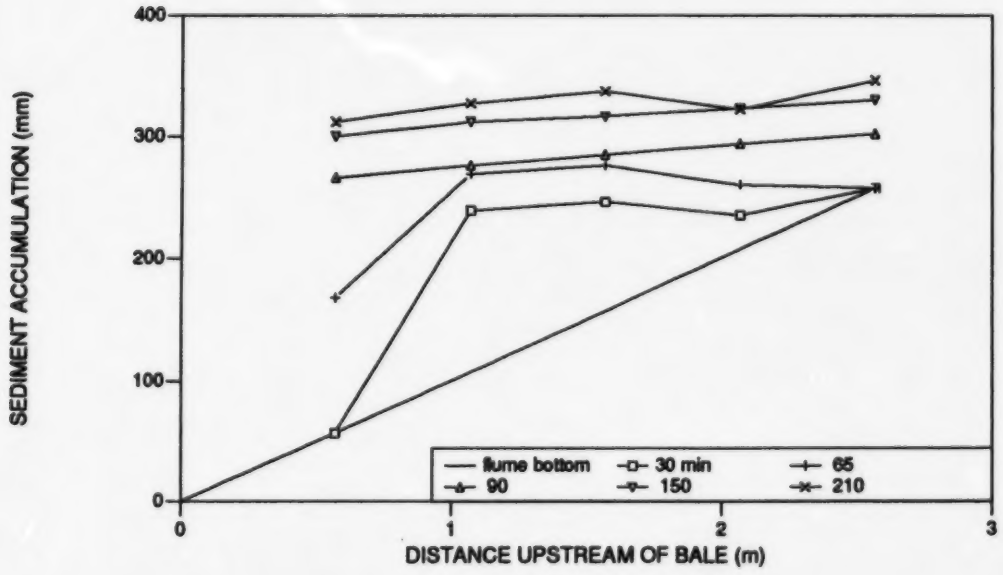


Figure 17 - Filtration efficiency and sediment profiles - Straw/vert.

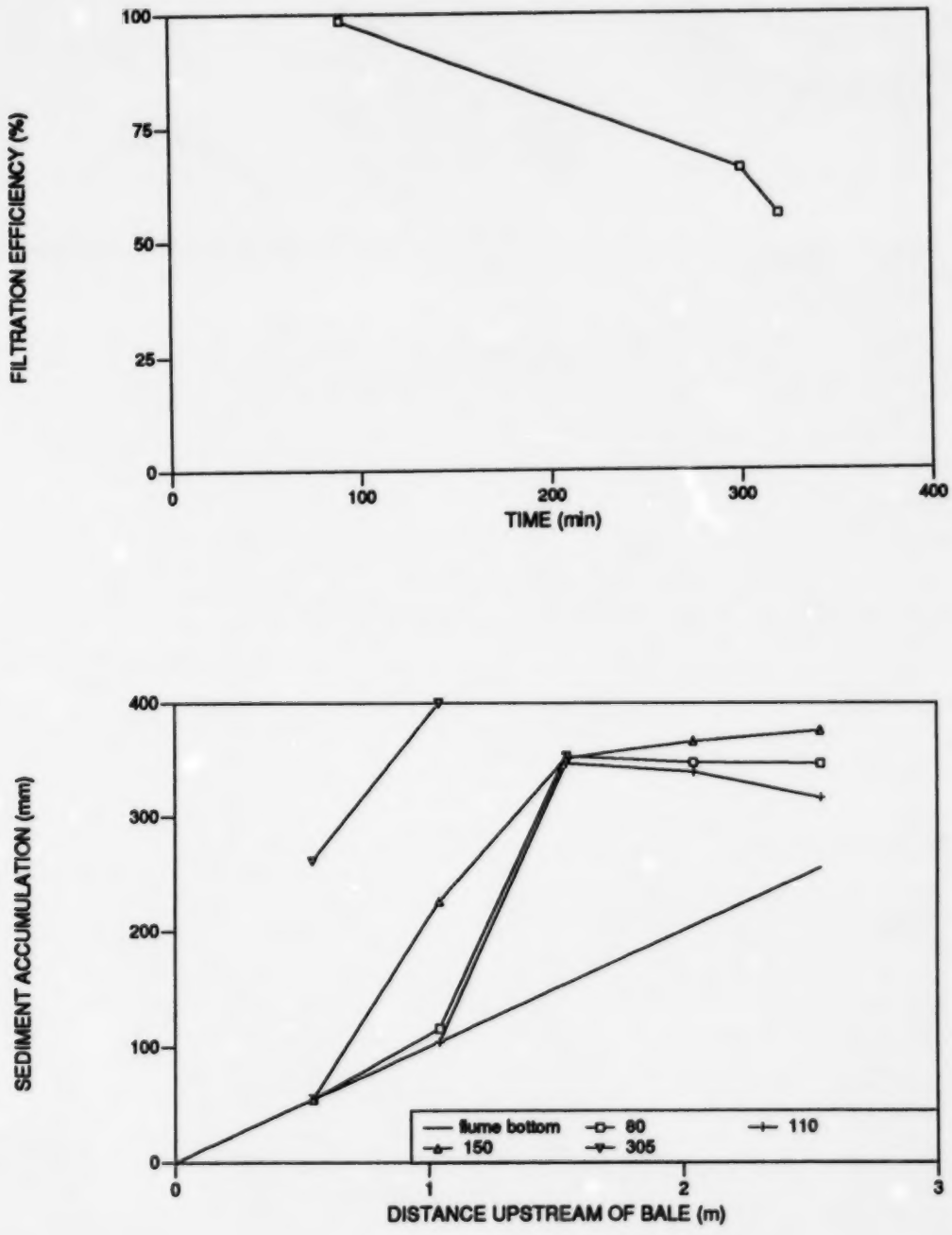
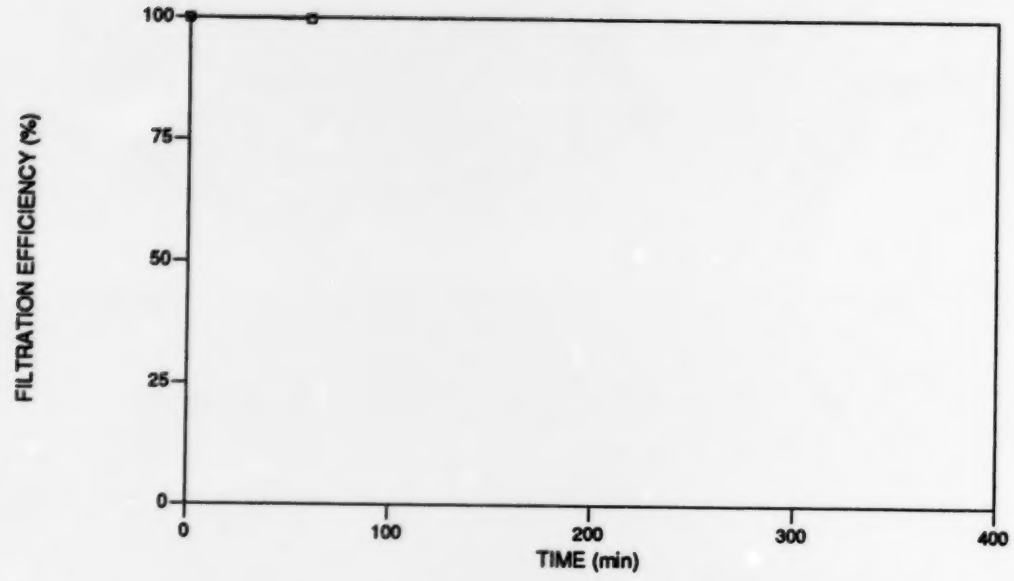


Figure 18 - Filtration efficiency and sediment profiles - Straw/vert.



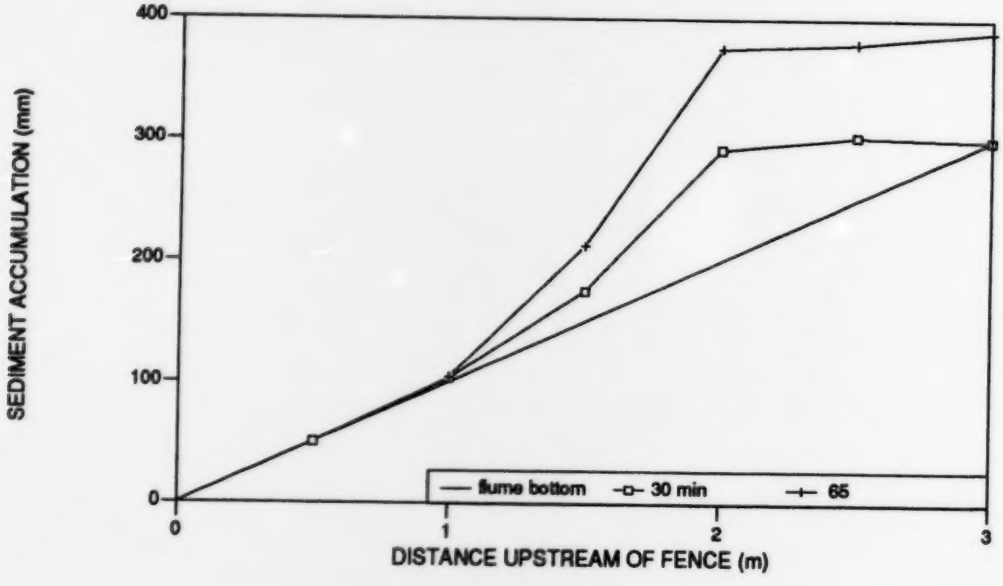


Figure 19 - Filtration efficiency and sediment profiles - Terrafix 370RS

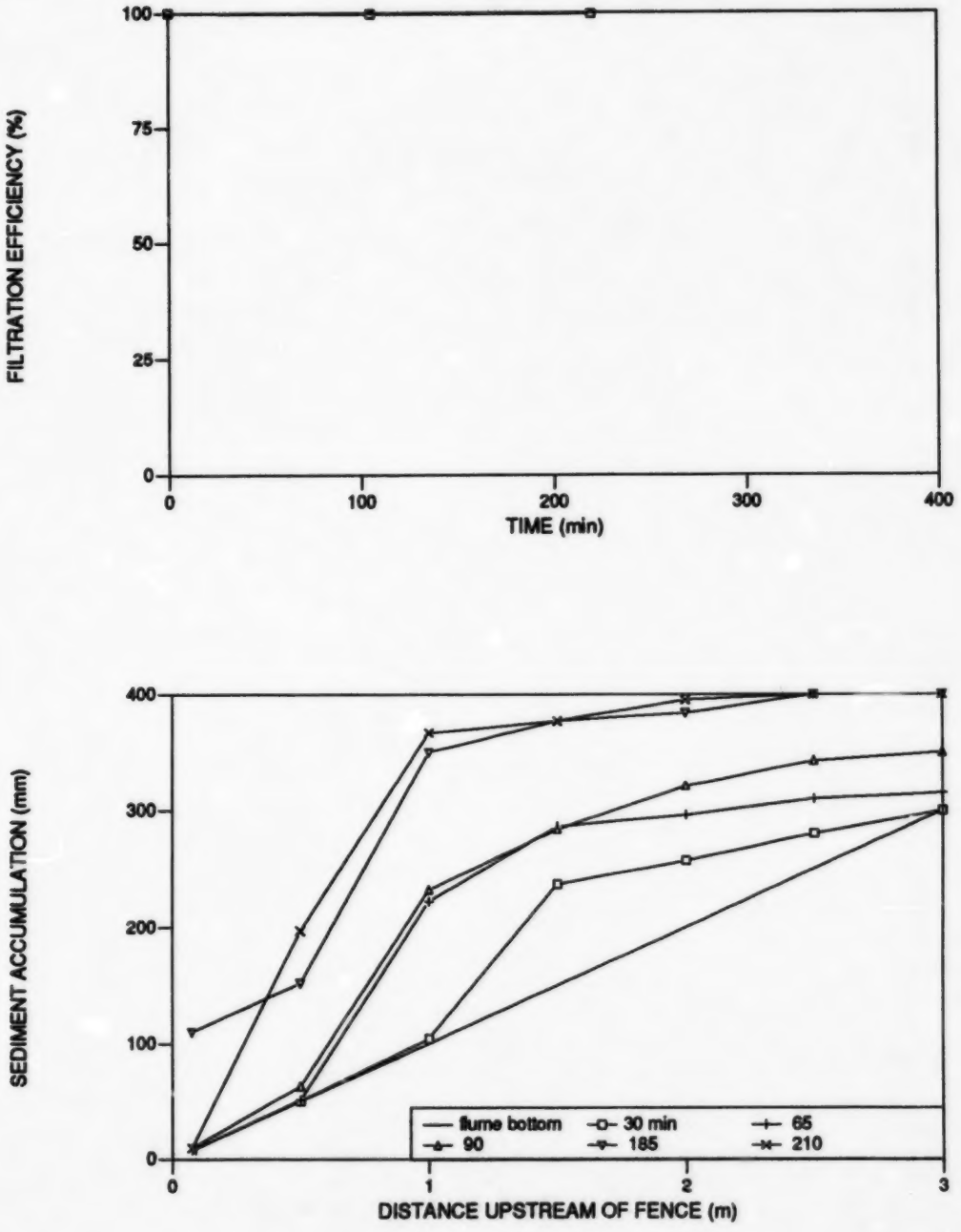


Figure 20 - Filtration efficiency and sediment profiles - Exxon 100S

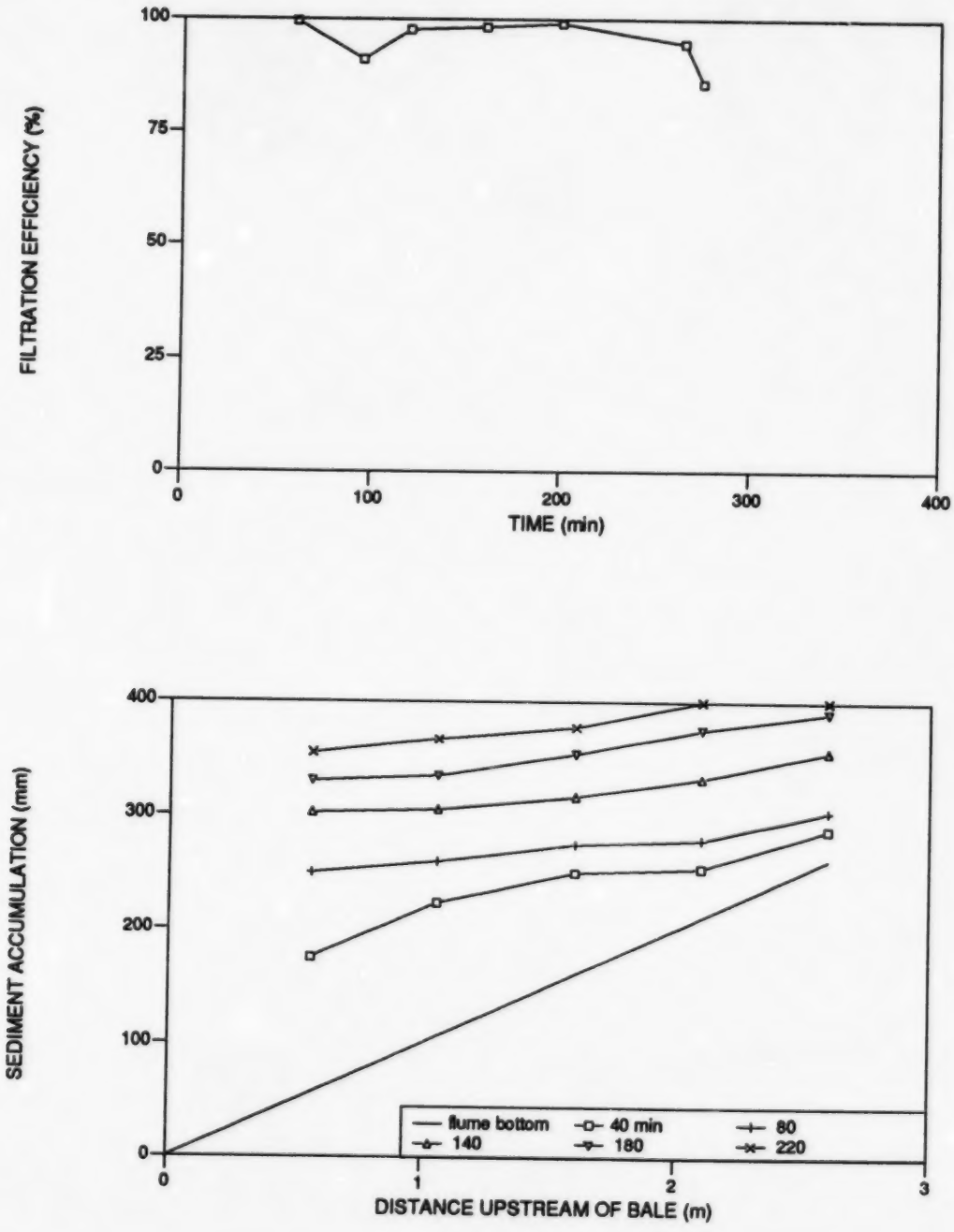
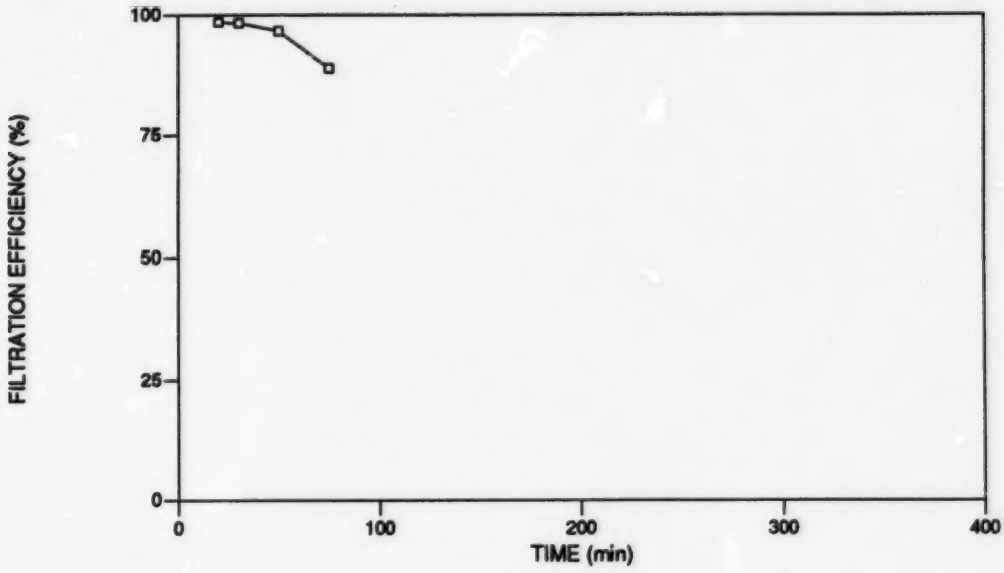


Figure 21 - Filtration efficiency and sediment profiles - Straw/hor.



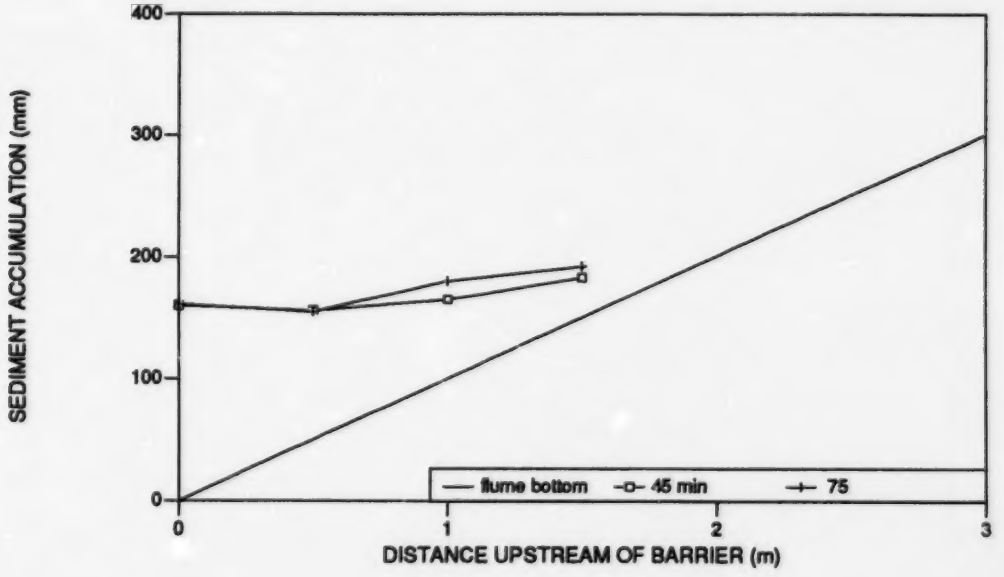


Figure 22 - Filtration efficiency and sediment profiles - Pee gravel

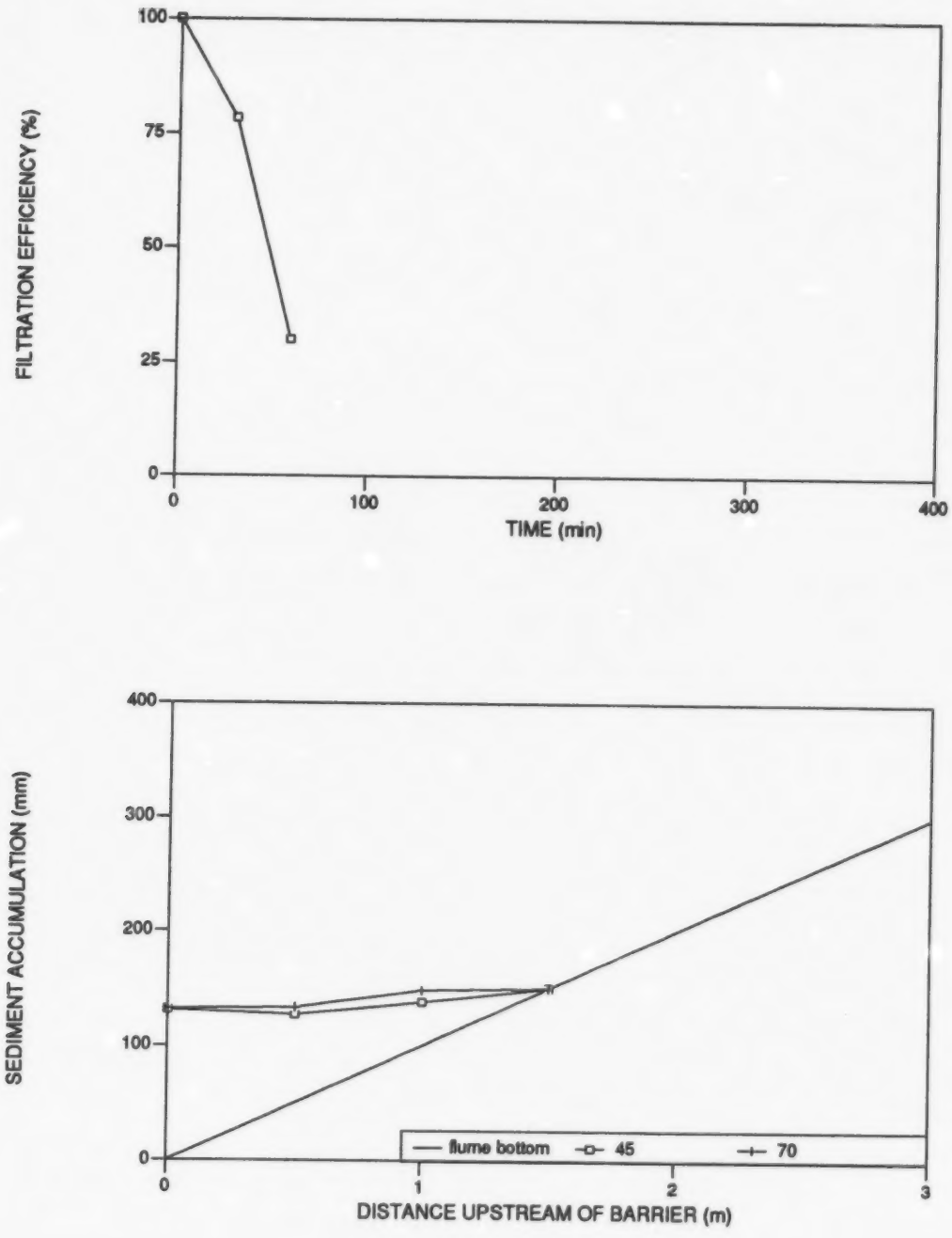


Figure 23 - Filtration efficiency and sediment profiles - 2 in. rock @ 10%

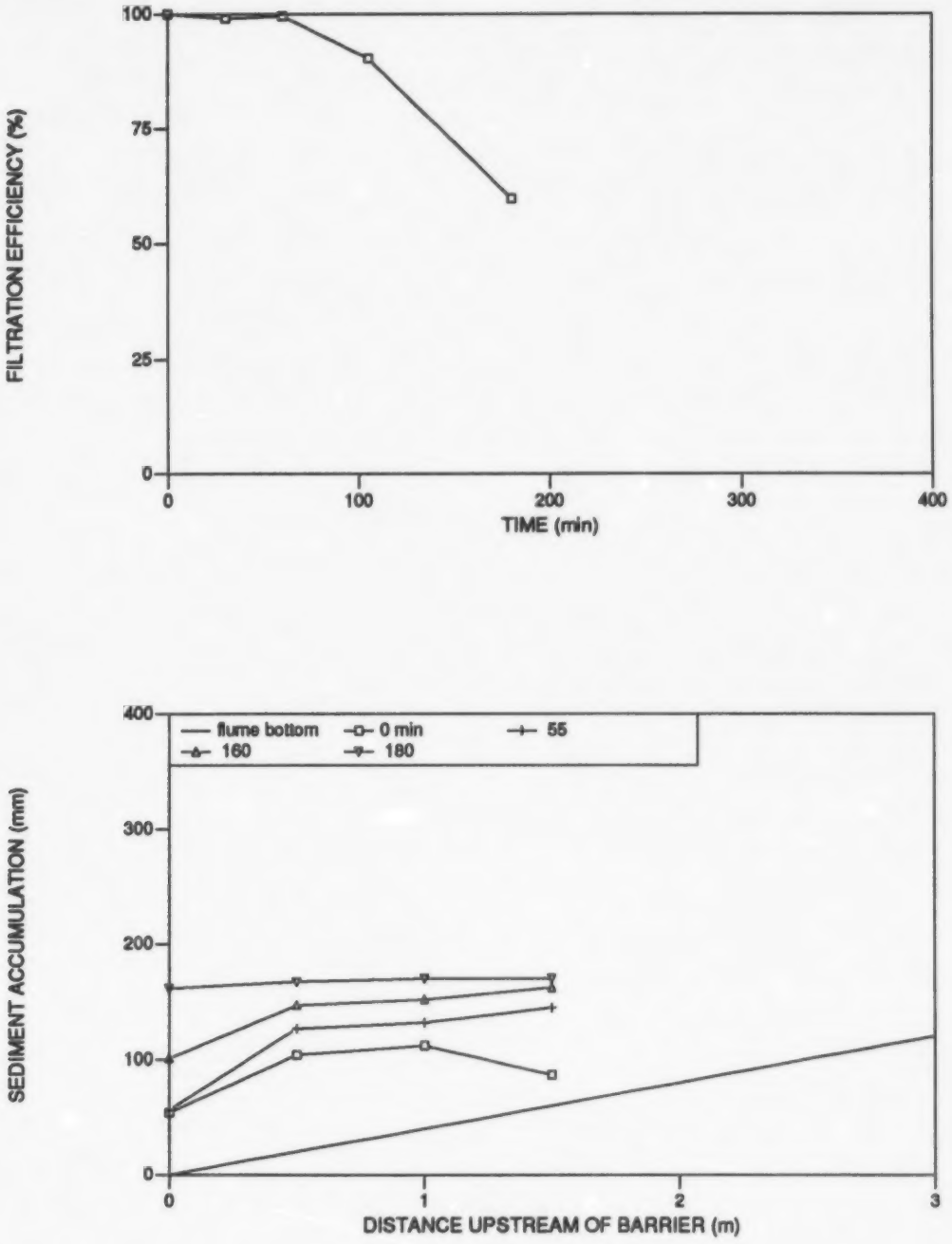


Figure 24 - Filtration efficiency and sediment profiles - 2 in. rock @ 4%

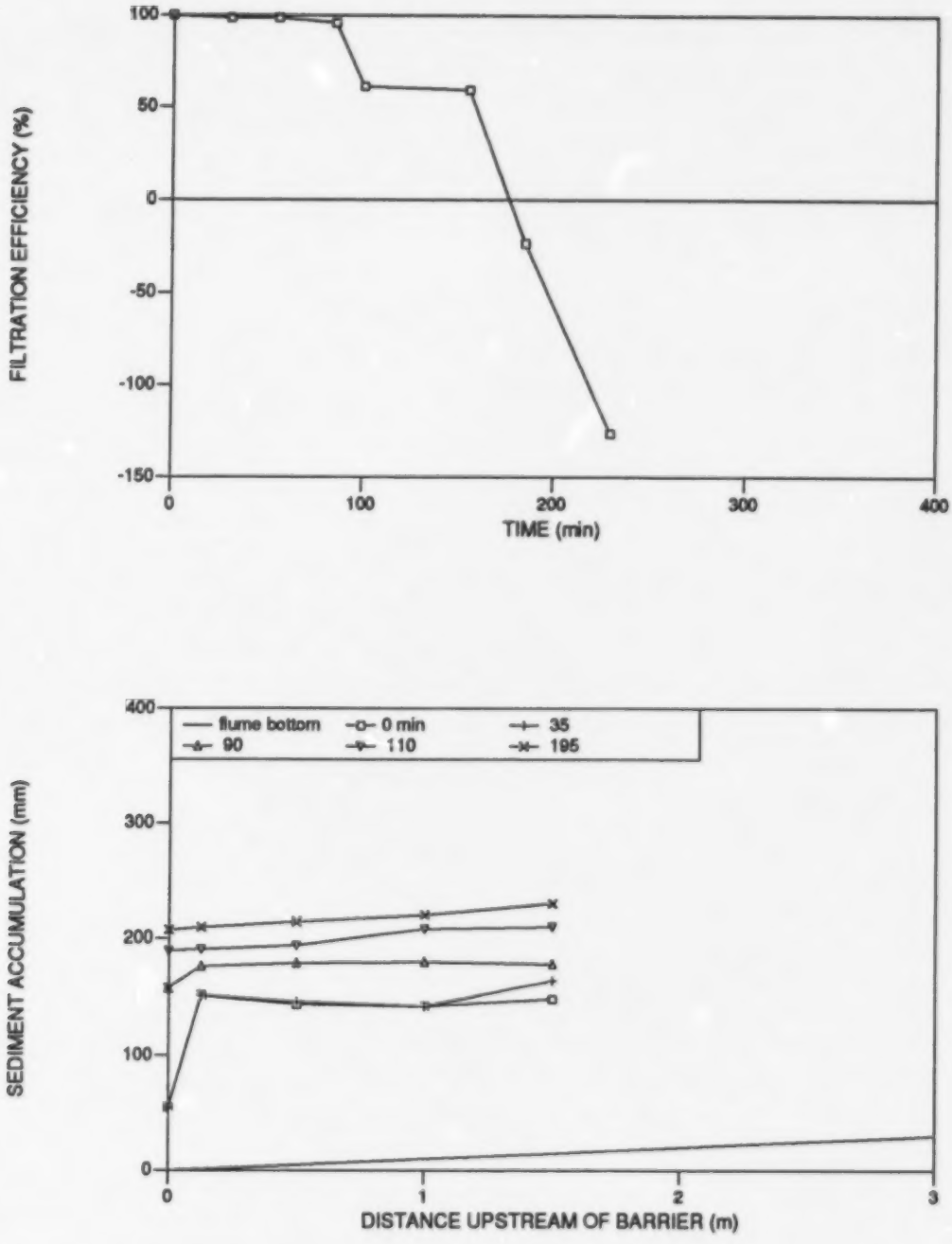


Figure 25 - Filtration efficiency and sediment profiles - 2 in. rock @ 1%

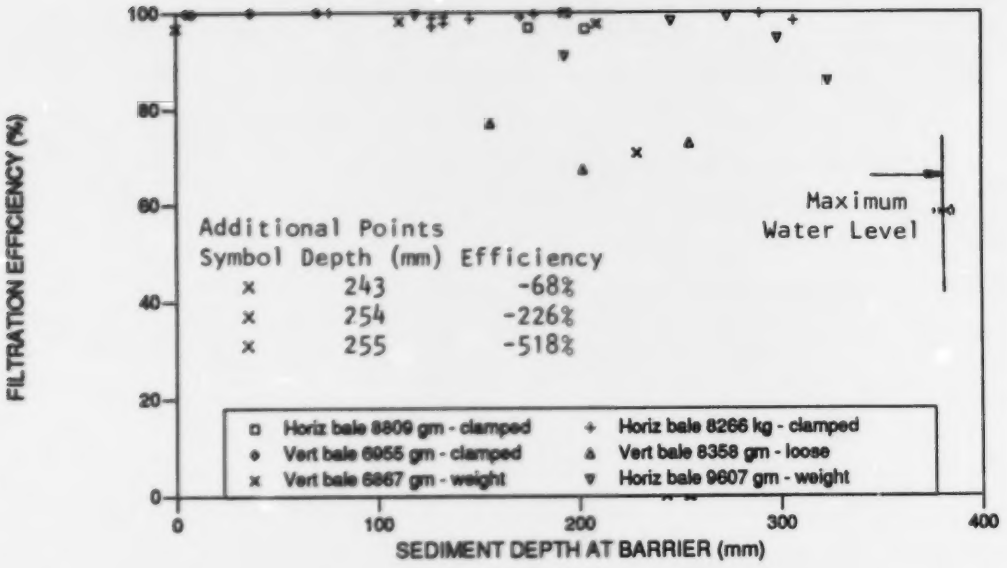


Figure 26 - Filtration efficiency versus sediment depth @ barrier

Straw bales

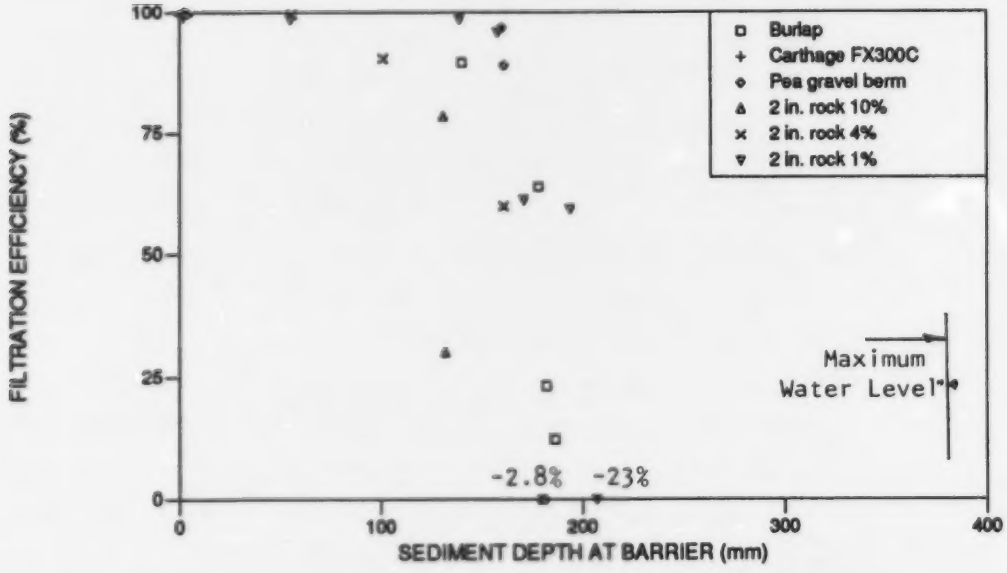


Figure 27 - Filtration efficiency versus sediment depth @ barrier

Fabrics and gravel berms

3.5. Discussion of Test Results

Based on all data and observations, the following generalised observations were made:

1) Burlap fabric EOS (Effective Opening Size) is too large, as the filtration efficiency falls well below zero at times. This was observed to occur as sediment would accumulate upstream from the fabric to a certain level and then quickly drop as sediment pushed its way through the fabric. Several such cycles were observed.

2) Carthage FX-300C, a woven geotextile, was greater than 99% efficient during the entire 350 minute run (experiment no. 27). This was due to the large amount of ponding.

3) The filtration efficiencies of Terrafix 370RS & Exxon 100S, were above 99% during their run times, but clogging caused the water to reach the maximum allowable depth of 380 mm (15 in.), after relatively short run times.

4) Straw bales, when firmly clamped into position, were greater than 95% efficient (experiment nos. 20, 21 and 25) as long as the bales were not overtopped.

5) The trapping efficiency of bales set with vertical stalks appears to be lower (experiment no. 25) than the efficiency for the bales with horizontal stalks. However, there is only one bale for comparison and this could simply be due to the density of the particular bale. The overall efficiency of both vertically and horizontally placed bales is over 99%.

6) If the bale is not placed firmly in the flume or if only a weight of 13 kg (29 lbs) (concrete block) is placed on top of the bale to hold it down (experiment nos 28, 29 and 30), the efficiency dramatically decreases. Since the bales were placed in a rigid channel, the straw could not be placed in a trench and packed with soil as recommended for field applications. It was difficult to hold the straw in place without leaving some holes which allowed short circuiting of the barrier. However, these

results point out the need that a straw barrier has to be very tightly installed in order for it to work at all.

The coarser sediments deposit furthest away from the barrier while the finer sediments are deposited closer to it. This is consistent with the process of delta building. This again points to the fact that only the finer particle sizes need to be considered when selecting the pore size of the barrier material.

Sudden and large changes in the flow rate can cause the filtration efficiency to drop dramatically. If flow is suddenly decreased or even stopped, and is later increased or restarted, a large slug of sediment can be swept to the barrier. While the variations in the sediment concentrations of the effluent were not measured for transient flow situations, the reduction in the trapping efficiency could be readily observed. For such transient situations, multiple check dams will serve to dampen the flow rate through the effects of additional storage. Also, in such situations, barriers made of filter cloth may be more effective because transient high flows may not last long enough to cause clogging to the point of causing overtopping.

It was also noted that sediment concentration in the effluent is usually not significant until the deposited bedload has reached the barrier.

As would be expected, the less permeable the fabric, the greater the water depth at the barrier, the greater the ponding area and the more efficient a particular barrier was found to be. However, the permeability of the fabric must be compatible with the flow situation, allowing enough flow to pass through without overtopping the barrier and to prevent clogging.

4. CONCLUSIONS

Burlap was found to be unsuitable for silt barrier applications due to inadequate ponding of the water upstream. The large pore space in burlap allows high rates of flow through the barrier, resulting in limited sediment storage due to ponding, and allowing all sediments reaching the barrier to pass through. Another problem with burlap is that it will quickly rot once installed. However, multiple layers of burlap may serve as an effective barrier if no other material is available and protection is needed for only a short period.

For most of the barrier materials tested, the bulk of the sediment was trapped due to the ponding effect rather than being directly filtered by the fence. Overtopping of the fence did not greatly reduce the trapping efficiency providing storage was available in the pond for the incoming sediment.

A steeper channel slope shortens the length of the ponding area. Because of this, the amount of sediment that could be removed from the flow is reduced, and the sediment (delta) reaches the barrier in a shorter time period. The slope and flow rate effect the filtration efficiency in that, once the sediment reaches the barrier, there is an increase in sediment which must be filtered (most was being trapped due to the decrease in velocity accomplished by ponding the runoff). Depending on the fabric EOS, the amount of sediment passing through the fence generally increased.

It was determined that initially, sediment was only trapped due to the decrease in velocity caused by ponding the water upstream of the barrier. The sediment accumulated in layers, with one layer building upon another, each layer beginning where the velocity initially decreased. Also, the coarser particles settled further from the barrier. For this reason, it may be reasonable to choose an EOS for a fabric silt fence by only considering the smaller particles which remain in suspension under the estimated peak flow. The EOS must also prevent excessive clogging of the fabric.

The data indicated clearly that with straw bale barriers, the need for proper installation is paramount. Those which were clamped tightly down in the flume had filtration efficiencies above 95%. However, when the bales were not clamped, the efficiencies decreased, sometimes below zero. The most likely reason for this is that piping occurred under these bales. Unsecured bales tend to "float", allowing much water and sediment to flow underneath. Proper in-

stallation of straw bale barriers and fabric silt fence barriers is the key to improving the filtration efficiency of the respective sediment control system.

Based on the literature and the experiments, it is much easier to install a tight barrier with geotextiles as compared with straw bales. However, based on the experiments, the filtration efficiency of straw is just as good as the efficiency of geotextiles when both are properly installed. However, the hydraulic characteristics of straw bales allow them to operate properly over a much larger range of flows than geotextiles because of the need to match a filter cloth permeability to a particular combination of flow and sediment characteristics. The hydraulic resistance of a straw bale is generally less than the hydraulic resistance of filter cloths, resulting in less ponding. However, as the sediment builds up in front of the barrier, some sediment is carried into the straw and clogs the bottom part of the bale. This raises the water level upstream, providing more sediment storage due to increased ponding. Although only one sediment size was used, this process is not likely to depend on the sediment characteristics for coarse silt or larger particles. It would take a lengthy experimental programme to establish all the inter-relationships and this may be considered for future work.

The rate of rise of the water level upstream from the fence was uniform for many of the runs. From these observations, clogging coefficients could be determined. Further investigation may reveal that clogging coefficients can be based on the soil characteristics and fabric characteristics (i.e. Effective Opening Size).

5. RECOMMENDATIONS

The literature provides detailed methods for the design and installation of silt fences. It is recommended that MTO adopt the methods described by Goldman et al. (1986) and ensure that field staff become familiar with the methods.

The need for the proper installation of silt fences clearly establishes the need for a rigorous field inspection and maintenance programme following their placement. It is recommended that MTO formally establish such a field inspection programme.

Obviously, the number of combinations of fabric, sediment type, flow rate, and sediment concentrations, not to mention unsteady flow rates, is unlimited. The experiments concentrated on comparing straw versus several other materials for only a limited range of conditions. It would be useful to extend the testing to include more fabrics, flow rates, and sediment sizes. It is recommended that the experimental programme be continued to increase the data base.

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APPENDIX A

Geotextile Producing Companies Contacted

CANADIAN SOURCES

Fiberworld Ltd.
(Dominion Textile Ltd.)
1400 Aberdeen St.
Hawkesbury, Ontario, K6A 2R4
(613) 632-2788
01-800-265-9331 ATTN: Don Moore

Lincoln Fabrics Ltd.
63 Lakeport Road
St. Catherines, Ontario, L2N 4P6
(416) 934-3391
ATTN: Garth Sullivan Wadsworth

Nilex Geotechnical Products
3448 93rd Street
P.O. Box 4063
Edmonton, Alberta, T6E 4S8
(403) 463-9535
ATTN: John Mooney

Terrafix Geosynthetics Inc.
69 Westmore Drive, Unit 3
Rexdale, Ontario, M9V 3Y7
(416) 745-7290
ATTN: Paul Hewell

Texel
485 Des erables, St. Elzear
Beauce Nord, P.Q., Canada G0S 2J0
1-800-463-8929
ATTN: Paul Anderson

UNITED STATES SOURCES

American Excelsior Company
850 Ave H East
P.O. Box 5067
Arlington, TX 76011,USA
(817) 640-1555
ATTN: June Morris

Amoco Fabrics and Fibers Company
Suite 550, 900 Circle 75 Parkway
Atlanta, Georgia 30339, USA
(404) 956-9025

Carthage Mills
1821 Summit Rd.
Cincinnati, Ohio 45237, USA
(513) 761-4141
ATTN: Tom Turner

Crown Zellerbach
USA
(206) 835-8787

Delaware Valley Corp.
502 Broadway 01841, USA
(617) 688-6995

Exxon Chemical Company
2100 River Edge Parkway
Suite 1025
Atlanta, Georgia 30328-4654, USA
(404) 955-2300
ATTN: John N. Paulson, P.E.

Foss Mfg. Co. Inc.
231-T Neck Rd., USA
P.O. Box 277
(617) 374-0121

James River Corporation
3720 Grant Street
Washougal, WA 98671, USA
(803) 297-7961
ATTN: Karen Stephenson

Menardi-Criswell Division
Hosokawa Micron International Inc.
Box 240 (13) Avenue, USA
Augusta, Georgia 30913-4699, USA
(404) 724-8241

Mirafi Inc.
P.O. Box 240967
Charlotte, N.C. 28224, USA
(704) 523-7477

Nicolon Corporation
3150 Holcomb Bridge Road
Suite 300
Norcross, GA 30071, USA
(404) 447-6272
Woodstock,Ont., Canada
(519) 539-9877

Phillips Fibers Corporation
P.O. Box 66
Greenville, S.C. 29602, USA
(803) 242-6600

Reemay Inc. (formerly DuPont)
Industrial Road P.O. Box 511
Old Hickory, TN 37138, USA
(615) 847-7031
ATTN: Pat Mayes

WebTec Inc.
P.O. Box 240302
Charlotte, N.C. 28224, USA
(704) 552-6722
ATTN: Dave Ellis